

ELECTRICAL ENGINEERING

JUNE

1944



AIEE SUMMER TECHNICAL MEETING, ST. LOUIS, MO., JUNE 26-30, 1944

KEEPING UP WITH *Electricity*

BACK ON THE JOB after a 25-year layoff are the original Westinghouse generators at Niagara Falls. These went into service in 1895 as part of the first great a-c poly-phase power system. Replaced in 1917, they were kept as standby equipment until the beginning of the present war. Rewound and reconditioned, they are now back in full-time service, delivering *more* power than when new.

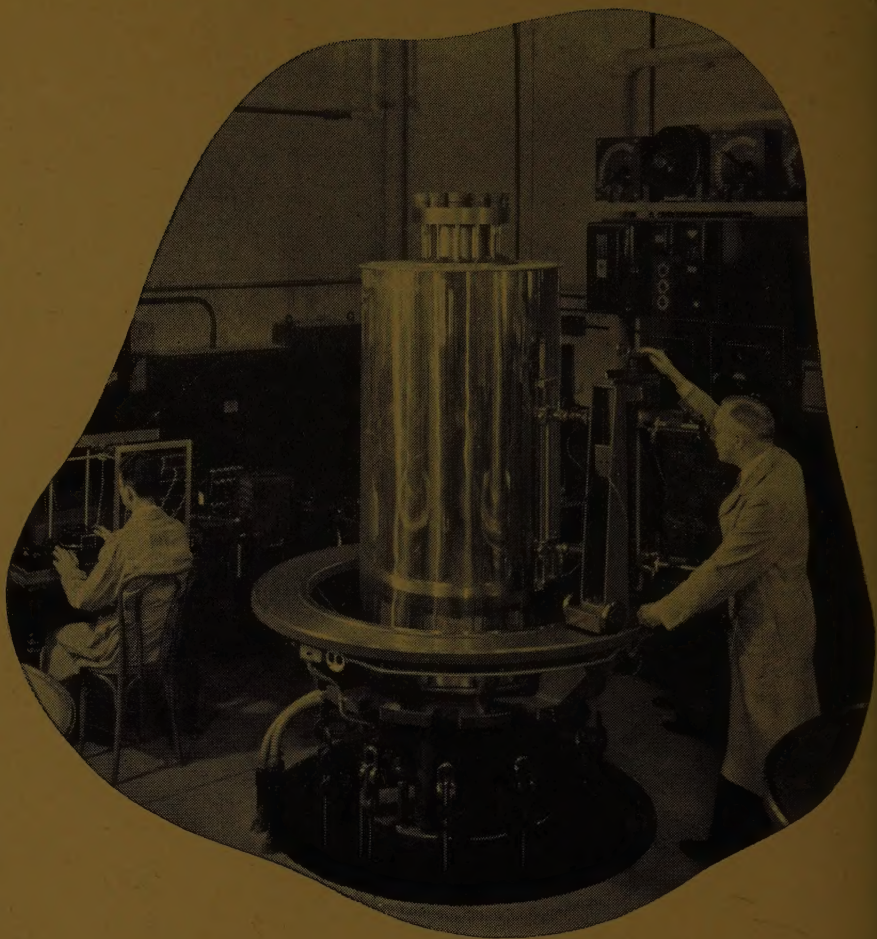
LIGHTS FOR HEAVYWEIGHTS. Those new super-bombers we've been reading about brought trouble on landing fields. Contact lights, sunk in the concrete runways, weren't built to stand the weight, so structural strength had to be increased to 200,000 pounds, without any change in dimensions. As late as 1942, 35,000 pounds was standard.

SIX-ROOM TRANSFORMERS—rather transformers as large as a six-room house are now serving a new war industry. They're rated at 75,000 kva each, and require 188 tons of steel, 130 miles of copper wire. Separately-mounted radiators, and use of Hipersil for cores kept down size and weight. Otherwise, say engineers, problems of shipment and installation would have been insuperable.

ELECTRONS BY THE POUND. One of the slide rule boys has figured out that nearly 4 pounds of electrons pass through each of the d-c terminals of a 10,000 ampere Ignitron rectifier in the course of one year. That's about 2,000,000,000,000,000,000,000,000,000 electrons, they tell us.

"MAKE WAY FOR A SAILOR" may be the new slogan in locomotives. Steam turbines, so efficient in ship propulsion, are being adapted for railroad use. Tests of one Westinghouse experimental 6,500 hp unit indicate a saving of one-fourth in steam required, compared to conventional reciprocating engines of the same power.

INSPECTING THE INVISIBLE. Tiny pinholes, invisible to the naked eye, mean defective tin plate and possible spoilage of badly needed food. A Westinghouse photoelectric device detects these defects every time, though the tin plate rolls past at 1,000 feet a minute. Flawed sections are automatically marked, to be later cut and removed.



Research behind gas turbines

The known simplicity and theoretical efficiency of the gas turbine has challenged generations of engineers. But the gas turbine as a *practical producer of power* could not exist until new alloys were created—alloys which could withstand high temperatures for long periods.

In the testing machine shown here, Westinghouse scientists tested alloys, subjecting them to stresses of thousands of pounds per square inch at temperatures as high as 1,000 degrees Fahrenheit. This was the research that provided better materials for steam turbines.

It was also an important step toward gas turbines. As the work continued, with new alloys and new testing machines, positive results were obtained at the high temperatures required for efficient gas turbine operation. *Thus, research developed the materials which make the gas turbine a practical possibility.*

Another example of the Westinghouse research that is constantly providing new tools for industry. Westinghouse Electric & Manufacturing Co., Pittsburgh 30, Pennsylvania.

WESTINGHOUSE PRESENTS: *John Charles Thomas, Sun. 2:30 p.m., EWT, NBC. "Top of the Evening," Mon. Wed. Fri. 10:15 p.m., EWT, Blue Network.*

Westinghouse

PLANTS IN 25 CITIES OFFICES EVERYWHERE

ELECTRICAL ENGINEERING

Registered United States Patent Office

JUNE

1944



The Cover: This new Douglas P-70 night fighter, an adaptation of the A-20 attack bomber, carries four 20-millimeter cannons. Electric equipment on military aircraft will occupy four sessions at the AIEE 1944 summer technical meeting (*pages 221-3*).

Photo courtesy Institute of the Aeronautical Sciences

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OUT OF TODAY'S RESEARCH
TOMORROW IS ENGINEERED



RECORD BREAKING HEAT WAVE

INDUCTION HEATING through powerful high-frequency radio waves is breaking records in speeding up production of bonded plywoods, tin plating and in other industrial applications.

Of prime importance to the efficiency and stability of such high-frequency circuits is insulation whose composition and strength is master of both power and heat.

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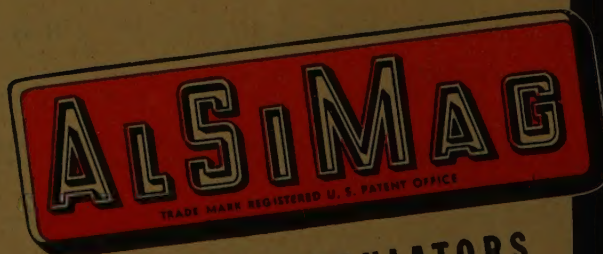
- High Mechanical Strength
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- Will Not Absorb Moisture
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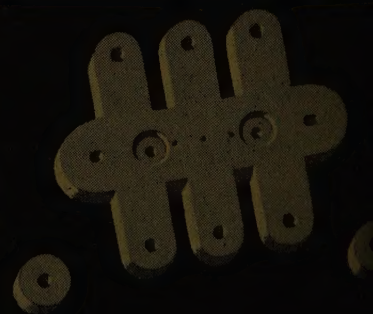
CHATTANOOGA 5, TENNESSEE



Army-Navy "E"
First Awarded July 27, 1942
Second Award: "Star" February
13, 1943
Third Award: "Star" September
23, 1943



CERAMIC INSULATORS



Meteorological Service for Electric-Power Systems

A. E. DAVISON
ASSOCIATE AIEE

THE ADVISABILITY of providing special weather forecasts for utilities and utility engineers, including communication and transportation organizations, was suggested by weather forecasters and climatologists early in 1943. It was recommended that utility engineers should indicate what special features of weather forecasts would make these predictions of special value to them.

As far back as 1934 and as recently as May 1940, conferences held in Harrisburg, Pa., by the Pennsylvania Electric Association,* and in Washington, D. C., aimed at the establishment by the electric utilities of additional weather-observing stations in those areas and greater dissemination and more purposeful use of weather forecasts. Assembly and dissemination of weather records by means of commercial teletype communication was recommended, a practice well-established in civil aviation in Canada, since an official typed record has certain advantages over oral or unrecorded communications, and receipt of teletype messages does not take employees away from other duties.

At the Harrisburg conference, a co-operative movement was set up whereby four observations would be taken by the electric utilities each day at 5 and 5:30 a.m. and at 2 and 2:30 p.m. Arrangements were made so that, in the Pennsylvania area, cloud cover, temperature, wind direction and velocity, and time of beginning and end of precipitation, would be furnished by the electric utilities from nine stations. These reports would be called for at centralized points by the weather bureau at 5:50 a.m. and 3 p.m. Special early-morning forecasts then would cover sky conditions, time and character of fog or precipitation, maximum and minimum temperatures, significant air movements, thunderstorms, glaze, humidity, and important air-mass movements for that day. Employees would be instructed in using these forecasts for establishing electric-service security and would learn the definitions, terms, and code procedures used by the meteorological office. At one of these conferences, the issuing of four Government weather maps per day was announced for some parts of the country.

Special forecasts for electric-power companies and wider dissemination and more effective use of these forecasts are advocated in this article. Effects of glaze storms, lightning, hurricanes, magnetic storms, fog, flood, precipitation, and high and low temperatures on electric service are discussed.

The advantages of long-time forecasts of precipitation and associated subjects received attention recently in a paper by Doctor Merrill Bernard, dealing with the classification of the various types of storms and the principles determining the maxi-

mum probable storm occurring in a particular drainage basin. Recently, the English research organizations have established by experiment the value of the public co-operation in locating accurately the paths and boundaries of electric storms.

The purpose of this article is

1. To record the meteorological needs of the electrical industry.
2. To suggest what studies, forecasts, and recordings should be available for establishing greater security in supplying electric energy, water, gas, community steam heat, electric rail transport, communication, and other like services.
3. To indicate what has been done already on a commercial basis by interested private organizations.
4. To secure more reliable estimates of immediate and longer-time water-power resources and storage of precipitation.

NEED FOR METEOROLOGICAL DATA IN ESTABLISHING SERVICE SECURITY FOR ELECTRICAL CONSUMERS

If the service security is to be established for electrical consumers, forecasting is essential to electric utilities—especially short 4- to 12-hour forecasting of the incidence, coverage, severity, and the paths and speeds of all storm fronts and atmospheric disturbances, including magnetic, glaze, and electrical storms.

Glaze Storms. Glaze storms in the past have created the greatest insecurity and caused the longest interruptions to service and the most physical damage to electric-power properties. About the only recognized means of protection against the mechanical overloading of electric transmission conductors by glaze and sleet is internal warming of the conductors, sometimes limited in applica-

Essential substance of an address presented at a joint meeting of the AIEE, Toronto Section, and the Royal Meteorological Society, Canadian Branch, October 25, 1943, and at a joint meeting of the AIEE, Montreal Section, and the Engineering Institute of Canada, April 27, 1944.

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The author acknowledges assistance in the preparation of this article received from engineers associated with the Pennsylvania Electric Association.

The statements and opinions expressed in this article are the author's and shall not necessarily be construed as being those of his employer.

*The systems operation committee of the Pennsylvania Electric Association, under the chairmanship of W. R. Hamilton, West Penn Power Company, Pittsburgh, Pa., and more recently under the chairmanship of E. W. Middleton of Pennsylvania Power and Light Company, Hazelton, Pa., has studied weather quite extensively during the past five years. A report on the work of this group may be secured from the Edison Electric Institute, New York, N. Y.



Figure 1. Number 2 copper wire ten days after storm at Van Hornesville, N. Y.

Ice has revolved with original icicles melting back and new ones forming

tion, since the necessary power current may not be available. If notice of from 4 to 12 hours is given for glaze or sleet storm, warming overloads frequently can be set up by rerouting of circuits, without great inconvenience to the stability and security of an electric system—even when the glaze deposits are only a probability. Two-to-four-hour notice of duration and severity of approaching storms would be sufficient for load dispatchers instructed in rerouting of power and doubling up of electric loads on lines in the forecast areas.

This warming up of conductors is most effective and most easily done when glaze is forming, because the formation of ice or rime on the surface of the conductors at that time is very critical. There is considerable evidence that a change of temperature of a small fraction of a degree at the surface of a conductor will check or prevent the formation of glaze. Instances have been noted where a water film was found between the ice coating and the de-energized conductor during a short period of sunshine. Evidently there was enough absorbed and locally reflected solar heat at the dull corroded surface of the conductor to account for the loosening of the ice coating from the cold conductor. Sometimes because of gravity, the ice coating, having quite irregular cross sections and shapes, actually rotates 90 degrees or so on the conductor.

If forecasts covering an area are not available, the electric-supply utilities find it difficult to discover what is going on at the center of a 50-mile and in some cases a 275-mile length of line between terminals. The terminals both may be outside the sleet area, and yet, because of various types of excessive mechanical loads, failures can occur near the center of the section.

Even if operators fail to make satisfactory use of forecasting or find it impossible to reroute electric loads, it still is important that forecasts of temperature and of light and heavy winds be made available while the ice is on the conductor, for the patrol and maintenance group must be kept on the alert. Phenomenal motions of the conductors may be expected, and both electrical and mechanical failures are likely to occur because of the action of cross winds on the stream-lined cross sections of the glaze or on the partially coated surfaces of the wires. Under certain conditions, the wind tends alternately to lift and to depress the conductor, with the result that, at the middle of the span, the conductor may be found in quite unexpected positions.

While short-time forecasts—4 to 12 hours—are likely to be most authoritative, nevertheless the more normal forecasts—12 to 36 hours—soon should be sufficiently authentic to be useful, especially for glaze storms. Longer-range forecasting—weekly to seasonal or annual—and cyclic phenomena now are used by some utilities in determining water-storage and like system requirements.

Some electric-power utilities, co-operating with the

limited weather forecasting already available, have set up operating procedures by which they “get ahead of the storm” and are eliminating, chiefly by load reallocation and rerouting, troubles expected during glaze storms.

Lightning. Thunderstorm days should be and are forecast, and, if intensities can be recognized by forecasters, then the more important storms should be featured in press and radio, but not necessarily to the extent that might alarm the average reader or listener.

At the present time lightning is the most frequent source of insecurity, outages, interruptions, and failures, within electrical works. Many actual interruptions to service due to lightning which affect the security of an electric system are of short duration; at times, however, important apparatus either is lost to the service or, requires an out-of-service period for repair. When lightning is forecast, some dispatchers remove temporarily from their systems certain lines which are relatively sensitive or exposed to lightning.

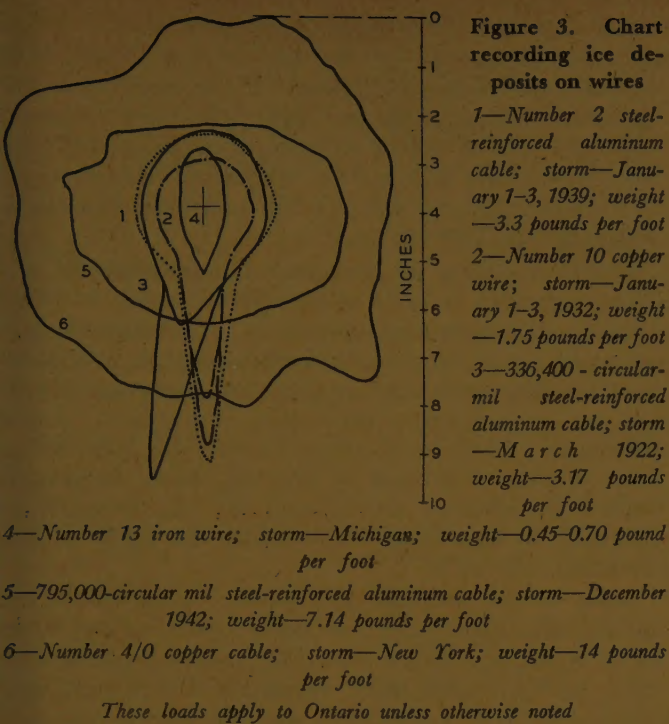
Lately, important transmission lines and stations can be protected from the effects of most lightning discharges near or striking directly at the power wires by installation of overhead or grounded wires, which requires extra investments of 10, 15, or 20 per cent, sometimes amounting to millions of dollars. However, since there is no positive security against the effects of lightning discharges, special operating setups should be established, such as the planning and making immediately available of alternative routes, closing of loops, and similar short-time securities or operating defenses, when storms and storm paths are forecast.

Hurricanes. The curving path of a hurricane or tornado originating in the tropics frequently can be forecast with some accuracy on the North American continent; however, these occurrences are very infrequent. The New England storm of September 16, 1938 caused damage which warranted special investigation as far north as the easterly counties of Ontario. It is indicated as twice crossing main 220,000-volt routes in Ontario while breaking up on the morning of September 22.



Figure 2. Route 20, east of Sharon Springs, N. Y., seven days after storm

Ice one inch radial thickness and icicles



Air-borne and marine traffic is rerouted, curtailed, and sometimes canceled on account of weather, but transmission works are always exposed, with the result that they generally are designed to carry the conductors, and a one-half-inch radial thickness of ice coating on them, together with a wind load equivalent to eight pounds per square foot on the cylinder. There are, of course, overload capacities in addition.

There should be available for design purposes an authentic record of the duration of and the areas covered by all winds in excess of 35 miles per hour along with coincident temperatures—in other words, an isoanemometric chart of lines recording the number of wind storms per year and their intensities. Some studies already have been made, the gaps in data having been filled in by estimations. The electrical societies are now arranging co-operatively for the dissemination of statistical information on the effect of wind upon operation and revenue.

Magnetic Storms. There are only a few recorded instances of magnetic storms which charged long power-supply lines electrically so as to cause relay operation. However, the electrical industry is still young, and the forecasting of this type of storm may require more attention in the future. The power-supply organizations are developing extensive communications of their own, costing in some cases as much as \$1,000,000. This system is being set up in an effort to establish every type of auxiliary service which will tend to insure electric-power service. Such a telephone system, as well as the commercial communication systems, will need the forecasting of magnetic storms. All such communication services almost invariably are affected seriously by these storms. Alerts and reroutes around forecast storm paths and areas are again the most available defense.

Fog. Fog, mists, and damp periods at critical temperatures may be related to glaze deposits and also are a problem in themselves, especially after long, dry, or frosty periods.

Fogs have an important bearing on aviation. In tropical areas fog can now be forecast so successfully that the despatching of important commercial aviation services often is deferred or withheld, for the sake of the safety and comfort of passengers, because of forecasting of fogs over a long route by as much as 24 hours in advance. Fogs in temperate climates may not be forecast so readily.

The power utilities are interested in fog data, especially for the winter months, since during a period of cold weather there is an accumulation of certain chemical particles or deposits which are attracted to or which form on the electrically charged surfaces of insulators, especially in urban areas. As a result, when a fog or light rainfall is experienced at the end of a winter season, flashovers are likely to occur more frequently than at any other time except during lightning storms.

Broadcasting of Forecasts. Meteorological stations in some instances already have forecast important storms, especially those depositing ice, sufficiently in advance to give time to reroute electric energy for the warming-up of the conductors; however, some machinery should be set up by which, under peace conditions, advance notice of storms will reach operating employees at remote stations. Featuring and popularizing forecasts of glaze and other storms in radio reports of weather as New Zealand did before this war and as the American military authorities are now doing, would assist materially. An employee, responsible for certain lines and services and having means at his disposal for keeping conductors warmer than usual for several hours by overloading who experienced an interruption, would be aided in his work by advance radio or press reports that glaze troubles were imminent in the district. Once it is established that these forecasts are reasonably authentic and immediately available, it will not be long before every operator will become quite glaze-conscious and will make full use, through reroutes, alerts, and the like, of this information.

There appears to be no end to the problems which develop out of weather stress with which the operators of electric utilities must cope and which forecasters could visualize. For instance, all the staff members of a power utility should be trained in taking precautions against stress of weather and in having all reserve and repaired equipment immediately available for service. Adequate broadcasting of authentic forecasts will make electrical repair, maintenance, and operating employees more weather conscious.

CLIMATOLOGICAL

Floods, Precipitation, Runoff and Gauging Stations for Water Flow and Levels. There are available from the Weather Offices considerable data regarding precipitation, some of which are used regularly by industry.

The gauging of streams, and like assemblies of weather data are arranged by or are now in charge of either those interested specifically in these water levels or of Government departments other than the Weather Bureau. There may be some duplication. Many students of meteorology believe that the possible effect of runoff and storage and level of ground water on climatic conditions should receive more careful consideration; however, for the purposes of hydroelectric utilities this branch of the work appears to be fairly well taken care of at the present time.

The long-time forecasting of annual precipitation, extensive drought periods, the lowering of ground-water

levels, and the cyclic nature of these variations, if it can be established, is important to everyone interested in weather. Those interested in power utilities request further forecasting over long-time periods and thorough distribution of more authentic recordings.

State power regulatory bodies are now using continuous records of precipitation, as issued by the water resources branch of the United States Geological Survey, to the extent that they know at a given time the amount of snow which is still to melt and to be added to estimated rainfall. Someone will say they have established "isobrechous" charts and lines. These surveys, which indicate the depth of snow on the ground and its water content, are used to estimate the probable water yield from snow cover during the ensuing spring runoff, and permit a forecast of the probable amount of water that may be stored.

The hydrometeorological section of the United States Weather Bureau, for three areas at least, has estimated the maximum possible precipitation—a very important forecast and estimate for engineers in charge of new water-power developments.

One of the earlier climatological researches which was made at the Experimental Farm at Ottawa was concerned with the extent, if any, to which agricultural soils are fertilized by snow water. This effect and an associated phenomenon—the effect which the absorption of losses due to corona and electric fields may have upon the surrounding air and on the soil when the resulting salts reach the earth—have never been reviewed thoroughly anywhere so far as the writer knows. All such information, in popularizing weather forecasts and recordings, could be assembled and distributed quite authoritatively by one organization. These data are frequently secured now for each watershed by different interests with some possible duplication—for instance, the same information might be secured by both the electric-power utilities and the foresters and lumbermen interested in spring log drives.

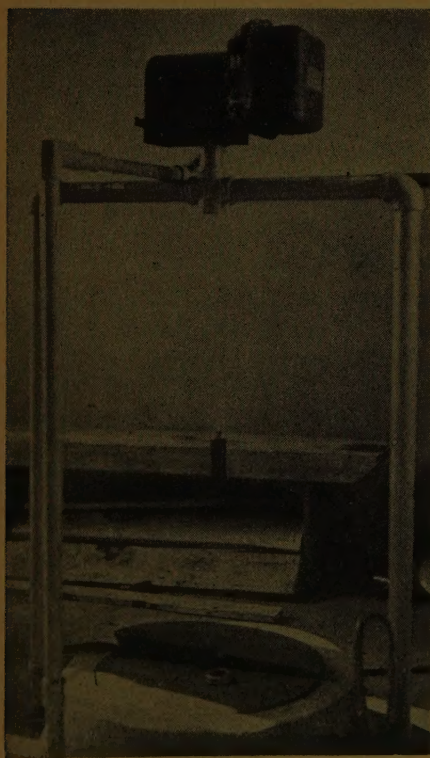


Figure 4. Float-type water gauge and well in forebay gatehouse

Long-Time Records of Temperatures—Frost Depths. Temperatures as low as -73 degrees Fahrenheit have been reported in Northern Canada. These are below the minimum temperatures for which designers of power and other utilities find it economical to design, but such low temperatures do not occur frequently enough, so far as is known now, to warrant the additional expense of designing especially for them.

Charts recording the incidence and frequency of low temperatures in areas in which electric power is being supplied should be kept up-to-date. The duration and extent of those low temperatures associated with snow coverage determine frost depths, and most utilities as well as agriculturists, need this information. Fence posts heave; so do poles and steel towers, the latter sometimes disclosing, because of heaving, quite unexpected forces. In northern areas, poles are set deeper than ordinarily in an attempt to minimize the effects of this distortion and strain.

Some of the facilities and weather data which are already established or are now being assembled and made use of by electric utilities and other private organizations might be used much more extensively if they were uniformly recorded, interpreted, and assembled, and disseminated both accumulatively and periodically.

The work done by L. J. Chapman on lines of highest and lowest recorded temperatures for an area, as reported in the *Canadian Geographic Journal*, September 1938, is an example of data that have been and can be issued under peace conditions. He records lines indicating the average number of days without killing frosts and other like information. These and other important charts should be kept up-to-date, giving the amount of precipitation to date as well as forecast, and should be issued periodically to power-supply utilities and similar organizations.

Glaze Racks. R. E. Jones of The Hydro-Electric Power Commission of Ontario standardized glaze racks in 1930. Some of these have been installed for observation in some of the northern United States and elsewhere and are being reported on by various interested persons. It is intended that the glaze shall be melted off and weighed for some specific length of standard round wire and that the weight of ice per unit length of wire shall be computed. Record should be made of the shape and contour of peculiar glaze formations on these racks, although this is not being done at the present time.

Lightning Records—Incidence, Severity and Types. The Weather Bureau and other interests have assembled data by which isokeraunic lines have been projected throughout the continent. These lines are not yet accepted as sufficiently authoritative, and it is hoped that some organization qualified to do so will undertake the work of making available more authentic information within the next ten years. These isokeraunic lines, necessary as they are, always must be quite indeterminate, because some reporters are disposed to record lightning if, on some summer evening, they see the reflections of lightning in some distant sky, whereas others may be disposed to report lightning only when it strikes nearby.

Utility Log Sheets; Co-operative Weather Recordings—Code Work. Records of temperature, wind direction, and general statements regarding the weather, as one part of routine reporting, reach the head offices of electric

ilities from many generating and other stations where operators are called upon to record more specifically the electrical conditions within a system. These data could be and are, in some instances, used by meteorologists; they may be reissued ultimately from the meteorological office as authoritative records over ten-year periods. Apparently some of these records now are telegraphed to headquarters in code, and short-time forecasts are returned.

STORM PATHS

Little work has been done on storm paths, and there appears to be much room for study. Of the available records, the more interesting features follow.

Effects of Geological Faults and Changes of Geological Structure. Small streams, sometimes flowing for a distance along geological faults or around the rim of a prehistoric or other tilted sedimentary basin, seem to account for more lightning flashovers on transmission routes which cross these areas than might be expected.

Very interesting studies have been made by French scientists on the interrelation of geological faults, normal air-earth electric currents, and lightning incidence; however, very little authoritative information has yet come from these studies, and more authoritative data are needed. This subject is open for further study and investigation by those who may have the time, opportunity, and interest in it.

Engineers recently have outlined in the English technical press local lightning experiences for which there does not appear to be any explanation other than geological and have been asking what effect geological formations and faults have on the incidence of lightning.

Storm-Path Records in Germany. Storm paths have been studied in Germany by Arendt and others, and some members of the meteorological services of the Reich comment favorably upon these efforts. If these reports can be relied upon, then it may be possible economically to lay out long transmission-line routes so that they will cross these major storm paths rather than parallel a concentration of them, wherever the terminals lie generally within a group of storm paths.

Storm Paths in Ohio. Brancato has recorded lightning storm paths in Ohio, many of which are straight line as in Arendt's work. Alexander has made somewhat similar studies some of which have not been published for that state.

Incidence of Flash Marks on Long Transmission Lines Varies With Geological Formation. Charts are available also which show the incidence of flashovers due to electric storms along a quite extended and important transmission route in Ontario; the incidence of these flashovers varies apparently with differing geological conditions. There is an excessive accumulation of flash marks which would appear to substantiate the statement that 80 per cent of flashovers are concentrated in certain areas constituting only 20 per cent of the length of the route. Charting storm paths and defining storm areas are two quite important items for operators of electric-supply systems, if the work by Arendt and others can be substantiated in other areas.

Personnel. Throughout the Allied countries, young men are being trained intensively as metallurgical technicians, as military store and equipment statisticians, and



United States Weather Bureau photo

Figure 5. Glaze storm in Illinois, December 17 and 18, 1924

as expert weather forecasters. During the late 1930's the Reich was giving young Nazis training to go abroad to administer occupied countries. Great Britain at the present time is actively training carefully chosen young men to join the diplomatic services and to work as public-administration career men abroad just as soon as World War II is ended.

Today civil authorities might well select three or more students in each academic year who, by intensive study at home and abroad, could create weather recordings, services, and forecasts for and within electricity-supply and other like systems. In Southern California, employees, trained initially under Major Krick and now possessing a master of science degree in meteorology, serve the utilities as load dispatchers. The application of meteorological knowledge is reported as effecting considerable savings.

Some, who have studied this situation intensively, say that meteorological science, as it develops, will reach a point where no government agency will be large enough to handle all individual requirements of business and industry—a point where individual meteorological counsel and advice would become so valuable in the conduct of many businesses that it would pay to employ meteorological consultants.

Weather Reports During Wartime. This review deals with postwar needs. Meanwhile, the supreme problem is the war—nothing else matters now in a relative sense. Distribution of forecasts and weather records during wartime, of course, is quite limited. However, there is no reason why we should not soon make greater controlled use, in the civil services and in business, of the great advances in forecasting for aeronautical combat that have been made during this fairly long war period. Weather knowledge, a very important tool in postwar planning, should be at work now.

All this is in the nature of postwar planning; however, we should keep in mind the statement made recently by statesmen on this continent that postwar plans should be put into effect now. It is a matter of record that some countries are doing just that. Just now, weather information is assembled in some countries by such services

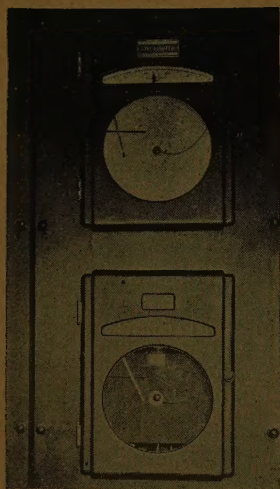


Figure 6. Recording equipment of diaphragm-type water gauge

as the meteorological office (prewar), civil aviation, military aviation, and privately controlled sources. All these presently should be combined to provide one improved authoritative service for all demands.

Radio, Radar, and Electronics. Several references to both popular and technical literature at the end of this article give some idea of the actual developments during wartime and of the postwar possibilities of radio and associated electronics in assembling weather data and in forecasting.

Popularizing Forecasting and Climatology. The joint task of engineers and meteorologists should be the popularizing of weather information. Making weather-conscious a public who have learned to take weather as it comes is important. Vetter in "Visibility Unlimited" has tried to popularize weather for airmen. He discusses new equipment, gives charts of rainfall, fog, and storm paths for the United States, and attempts to create weather-mindedness by pointing out what may be expected when observers find the temperature approaching the dew point. Thousands of active service men and women will return to civil life quite weather-conscious. Many of them of necessity have studied weather so intensively that with future training they might assist in some capacity, professional or otherwise, in meteorological undertakings which industry may initiate in the future.

One electrical supply organization, according to a contributor, has developed the following course of instruction for its operating staff. First, they review weather conditions prior to several more important sleet and glaze storms during which they were inconvenienced, as a guide and indication of what might happen in the next storm. In this review, they indicate the very critical nature of glaze formation since during that period very minor changes of temperature within the conductor will tend to keep glaze off its surface. Means of preserving transmission service once glaze has commenced to form on unheated objects are discussed, the principal procedures being short-circuiting and the use of higher-than-usual electric currents. They record, in their circular instructions, those stations from which, by arrangements in advance, information on glaze formation can be secured, and they recite those system and intersystem agreements which already have been issued to facilitate glaze rejection and removal.

Forecasts for Engineers, Utilities and Industry. There has been set up experimentally in one area a daily special

forecast for a six-months trial period for engineers and industrialists. Matters in which the utilities appear to be most interested will be discussed and predicted more confidentially than is possible in the more routine forecasts. In each case, these forecasts will cover at least two succeeding days. During this trial period, the forecasters are expected to familiarize themselves with the requirements of the utilities, and there will be an opportunity to discover how closely to the engineers' needs a qualified forecaster can predict. Out of this co-operative effort, there might develop a routine service for all interested organizations.

A similar experiment in a more specialized forecast service for utilities will be conducted by the Weather Bureau in the Chicago area. Routine forecasts of a special co-operative nature have been made for electric-power companies in this area since 1940, but it is believed that a more personalized service and a better knowledge of the specific needs for weather service will result in further improvement. A rather comprehensive survey of the entire industrial forecast problem in this area was made in December 1943. It showed the value of forecast liaison work and also the need for group industrial forecast specialists.

What Can Electrical Utility Operators Do About Weather? As previously stated, planning engineers and load dispatchers can lay out and file in a dispatcher's office specific alterations of routine operation so as to create most satisfactorily both intersystem and intrasystem defences against a hypothetical but typical storm or against storms forecast in only one part at a time of the area served. These special operating setups can be used, for instance, for a glaze storm predicted as about to pass along a recognized storm path down a river valley, or for thunderstorms forecast as being segregated during the early part of a storm period to one side of a lake, and during the latter part of the storm period to the other side of that lake. So much for planning.

Once such a storm is definitely predicted by the meteorologists, the routine set up in advance can be established by the dispatcher, along with other evidently necessary preparations listed as follows:

1. Put everyone connected with the system on the alert, apart from whether they are on duty at that time or not.
2. Return all equipment under repair to service with temporary connections. Do this even for a noon-hour period and always for a week end.
3. Reroute commercial loads as promptly as possible to the temporary and inter-system setup that has been planned and from experience, which offers, in the opinion of the dispatcher, the best defense against the type of storm predicted.
4. Recall or temporarily assign vacationing and off-duty employees and like absentees to key positions or to strategically located reserve pools.
5. Man remote-control switches.
6. Notify important and interested customers to stand by for load adjustments without interruption of service, and for the possibility of accidental interruptions.
7. Stand by for forecast cancellations and revisions and for the all-clear weather notice before restoring normal economic-system operating setup.

What Savings May Be Effectuated if Maximum Advantage Is Taken of All Available Weather Information? Meteorolo-

ts, especially those on the Pacific Coast, have established substantial savings for agriculturists who avoided expense on account of what otherwise was an evident emergency due to drought. It is also reported that one manufacturing company saved approximately \$10,000 annually by making use of predicted minimum temperatures. There may be opportunities of establishing similar savings within electrical utilities in future, since costs of restoration of lines and works sometimes amount to millions of dollars. All these restoration costs cannot be avoided by use of authentic weather information; however, part of most poststorm expense, inconvenience, and hazard could be saved or avoided, as in the case of the agriculturists.

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Industrial Research Under Free Enterprise

LOUIS RUTHENBURG

LET US first define our terms. "Industrial research" is subject to more than one interpretation, and so is "free enterprise."

In this discussion "research" will be used in its broadest aspect, without distinction between fundamental and applied research, between scientific and engineering research, or between research and technology.

Not long ago I asked Charles F. Kettering to tell me what he thinks is the most important aspect of research under current conditions. With characteristic simplicity and clarity, he said: "I think there is one thing which has come out of the war that is most important from the standpoint of research in industry, and that is the importance of having *samples*. Industry was able to turn over to war work and get production going in a short time because *samples* were available." Doctor Kettering pointed to the need for thorough understanding of the procedure of sample making as distinguished from the techniques of manufacturing or multiple production. He said that the process of making "samples" is akin to the creative art of writing a book or of composing music and that the process of manufacturing corresponds to printing books or to making phonograph records. Without too much regard for technical distinctions among the various phases of research, let us think of research as all of the processes involved in the development of "samples" from which industry can make unlimited copies to meet the unlimited needs of the people of the world. So much for our definition of research.

Now let us take a look at "free enterprise," which, incidentally, is not included among the much-discussed, "Four Freedoms." Modern politicians use a very effective technique, which involves the selection and frequent repetition of words and phrases that do not necessarily create logical or even truthful impressions but have profound emotional effects upon the people who hear and repeat them.

"Freedom from want and fear" have strong emotional appeal. But these are not fundamental freedoms; they are objective and secondary. We cannot be endowed with them; we can only strive to attain them. Without fears and wants mankind would degenerate and perish. Such facts, however, do not diminish the emotional appeal of "freedom from want and fear."

There does seem to be one fundamental freedom which we gropingly attempt to define. It is not mentioned among the four freedoms. We hear a great deal about "free enterprise," but a recent Gallup poll indicates that

Freedom of opportunity, inherent in the makings of the United States has fostered research and invention. Research methods which through industry have provided us with the highest material living standard of any country in the world, conserved our resources, and helped insure our national future, should be applied equally to the fields of political economy and jurisprudence, urges this author.

only three out of ten people have a clear conception of what is meant by it. Perhaps there is a better expression for that fundamental intangible freedom for which we are presumably fighting the greatest of all wars. Among the answers to the Gallup poll, one of the best came from a truck driver in Oklahoma. He said: "It means a hell of a lot to me. I don't believe in this stuff of telling a

man what he can and can't do." The same thought was expressed years ago in more scholarly language by the late great Supreme Court Justice Brandeis when he said: "The makers of the Constitution . . . sought to protect Americans in their beliefs, their thoughts, their emotions, and their sensations. They conferred, as against the Government, the right to be let alone . . . the most comprehensive of

rights and the right most valued by civilized man." Patrick Henry defined freedom in no limited sense when he said so simply and so dramatically: "Give me liberty or give me death."

Another definition for this intangible, fundamental freedom is that it is the right of free men to work when and where and for whom they please, without restriction or penalty, so long as employer and employee agree, and the right to conduct a business as one sees fit so long as the operation of that business is not in conflict with the public interest. In brief, this freedom for which we are fighting this greatest of all wars—the freedom that brought supremacy to our country—this fifth freedom—is *freedom of opportunity*. I believe it is that inclusive fundamental freedom which we inadequately describe as "free enterprise."

INFLUENCE OF BASIC FREEDOM ON RESEARCH

Freedom of opportunity was inherent in the genesis of the American Republic, which brought about conditions almost miraculously favorable to conception, gestation, and birth of invention. The founding fathers freed their countrymen from restrictive influences, bestowed upon them compelling incentives, and created an environment conducive to effective co-operation on the part of all elements in a complex society. Moreover, the American Revolution and the adoption of our Constitution were almost exactly coincident with the great inventions that gave birth to the Industrial Revolution. Among other great incentives for research and invention, the Constitution of the United States provides that Congress shall have the power "to promote the progress of science and the useful arts. . . ." The first act of Congress, passed April 10, 1790, placed the granting of patents. Thomas Jefferson, as Secretary of State, personally examined many petitions for patents. For many years patents were signed by the Presidents of the United States.

Essential substance of an address presented at the winter meeting of the Industrial Research Institute in Rye, N. Y., January 28, 1944.

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Such blessings of opportunity and incentive were conferred upon an ingenious, restless, resourceful people, and search, in the inclusive sense of our definition, grew apace. Inventions increased in geometric ratio. Productivity per unit of man power was in consequence multiplied. The American mass market developed ever increasing buying capacity through widespread distribution of the fruits of increased productive efficiency among consumers, workmen, and investors. Profits and savings were reinvested freely to expand business and to exploit new inventions. Demand was stimulated and directed by increasingly effective salesmanship and advertising. As a consequence of such cumulative and co-operating forces, the average citizen of the United States for many years has enjoyed the highest material living standards of any citizen of any country at any time in the world's history.

THE PROVING GROUND OF WAR

In the terribly tense days that followed immediately after Pearl Harbor a distinguished economist of German birth and international outlook made this prediction: "History will record the achievement of American industry as the outstanding miracle of the war." Evidence since accumulated has proved conclusively the soundness of Doctor Stolper's assertion. After ten years of political meddling, restriction, and persecution of American business and without adequate prewar preparation, our country now is producing war materials unmatched in quantity and quality by those that the German war machine is manufacturing after years of preparation and the application of the utmost effort of enslaved countries and individuals.

American research had grown prodigiously in the interval between the 1914 and 1939 phases of the World War. It is said that between 1920 and 1940 American industrial-research laboratories increased from about 100 to more than 2,200, and the number of American research workers from 7,600 to over 70,000.¹ Moreover, the most effective organizational procedure, in traditional American pattern, has brought the fruits of research into immediate and effective war use. The National Defense Research Council, the National Academy of Science, the National Research Council, the National Inventors Council, the several engineering societies, and—under the War Production Board—the Offices of Scientific Research and Development and of Production Research and Development, all have contributed directly toward the accomplishment of the "miracle" which Doctor Stolper predicted in late 1941. The very recent award by the Ordnance Department to the Society of Automotive Engineers is indicative of close association and effective collaboration between Governmental departments and scientific and technical societies.

Yes, we had the "samples" when we were confronted suddenly with the tremendous problem of converting America's scientific and industrial machinery from purposes of construction and the satisfaction of human needs to those of destruction, and we had a century and half of intensive experience in acquiring the know-how of both research and production. We are beneficiaries of rich contributions given to our culture by the Eli Whitneys, the Robert Fultons, the Samuel Morses, the Alexander Graham Bells, the Cyrus McCormicks, the duPonts, the Westinghouses, the Edisons, the Pupins, the

Henry Fords, the Coolidges, the Langmuirs, the Millikans, the Ketterings, and thousands of their spiritual kinfolk. Ingenuity, versatility, and adaptability are important elements in our rich heritage of freedom of opportunity. The "samples" that were available to us for war purposes were not simply "samples" of airplanes and tanks and guns and munitions. There were "samples" of machine tools, dies, jigs and fixtures, techniques of processing, and tool design—innumerable "samples" available from the great storehouses of knowledge and technique that have been filled by chemists, biologists, physicists, and technicians from thousands of laboratories and factories during the century and a half of our national existence.

Conder C. Henry, Assistant Commissioner of Patents, said:

"It is a matter for national thanksgiving that we not only had available a vast storehouse of knowledge as represented by the 2,275,079 patents which had been granted prior to Pearl Harbor, but also that our citizenry have been trained and are accustomed to invent."

THE BENEFICIARIES OF RESEARCH

Our industrial heritage, stemming from and nurtured by research, is serving our country well in its hour of greatest peril. That fact is immediate and dramatic. For many decades research has been making vitally important contributions to the American standard of living. In the long view that fact, although less dramatic than our march toward victory, is more significant in its implications for the future. It is significant that those industries which have engaged in extensive research are the ones that have made the most generous contributions to the public good and incidentally to the welfare of their own employees and stockholders. There should be more general understanding that research benefits the people of the nation and of the world in far greater degree than it benefits the scientist or the inventor. It should be understood, moreover, that the business institution that multiplies and transmits the "sample" developed by research serves principally as a mechanism of transmission between the inventor and the people and is a beneficiary of research only in a secondary sense.

Michael Pupin's autobiography, "From Immigrant to Inventor," is one of the most inspiring books I have ever read. Among his many important inventions was that of applying inductance to telephone circuits, which completely revolutionized the art of telephony. In commenting upon the value of that invention, Doctor Pupin said:

"A vice-president of the American Telephone and Telegraph Company, who is a very high authority in telephony, informed me recently that one way to describe, roughly, the value of the invention is as follows: If during the past twenty-two years his company had been compelled to extend its network of conductors so as to give, 'without employing my invention, the same service which it is giving today, it would have had to spend at least one hundred million dollars more than it has actually expended.' But after quoting him I wish to call attention to a fact which the public often overlooks. I ask, where are those one hundred million dollars which the invention has saved? I know that not even a microscopic part of them is in the pockets of the inventor. I have figured out also, with the same accuracy with which I once figured out the invention, that those hundred million dollars are not in the pockets of the telephone company. They must be, therefore, in the pockets of the American public. The invention made it possible to give the

telephone service, which is now being given, at a lower rate than would have been possible if one hundred million dollars more had been spent. *Every good invention benefits the public immeasurably more than it benefits the inventor or the corporation which exploits the invention.* I certainly consider myself a public benefactor, and the National Institute of Social Sciences called me so when it gave me a gold medal almost as big as the full moon. But this gift would have made me much more happy if the Institute had at the same time given another gold medal to the American Telephone and Telegraph Company."

William D. Coolidge, General Electric Company's director of research, recently made the following comment:

"It is not often possible to evaluate in dollars the benefit to the public from industrial research, but this lamp development lends itself to suggestive figures. It can be shown that, if the American public had had to produce with the lamps of 1900 the amount of light it actually used in 1942, the increased cost would have been approximately \$4,000,000,000. Of course the public would not have spent that huge sum for light, but how great would have been the cost of inferior lighting in reduced safety and efficiency in our war industries and in reduced comfort and convenience in our homes cannot be estimated. Neither can we estimate how far below its present magnitude and efficiency would have been the electrical industry."

Economists generally agree that the automobile industry has been one of this country's greatest creators of wealth. It has set in motion other great industries—road building, the petroleum industry with its many ramifications, the great rubber industry—to name but a few. It has contributed importantly to the tax industry. It has been estimated that in the '20's the automobile and associated industries gave employment to ten per cent of our working population. Intensive research has been characteristic of this modern group of American industries. An uninterrupted stream of inventions and results of research constantly has energized and renewed these industries.

A little more than 30 years ago Kettering contributed the electric starter. At that time the automobile industry was simply an interesting infant. Women did not drive cars. There were no concrete roads nor low-priced closed bodies. The wealthy few who owned automobiles stored them during the winter months. The electric starter gave the industry tremendous stimulation. It multiplied the number of potential owners and drivers. Instead of being a facility available only to strong and venturesome men, the automobile became tractable in the hands of women and children.

There followed rapid development of our great system of concrete roads, filling stations and service depots, low-priced closed bodies, constant increase in volume of production with miraculous reductions in price, remarkable improvements in tires. In 1910 a good automobile tire would give about 2,500 miles of road service and cost \$25. Now a tire of the same size, but containing more rubber and capable of being driven at much higher speeds, usually gives between 15,000 and 30,000 miles of service and costs initially only half as much as its 1910 predecessor. Synthetic rubber now promises to supersede natural rubber and to establish new high standards of service.

Then came other revolutionary changes. Gone were the old multiple coats of slow-drying paint and varnish before the advances of modern lacquer finishes. From the newly established General Motors Company research

laboratories came Kettering's and Midgley's discovery of ethyl gasoline. From the laboratories of petroleum companies came new processes which led to more economical production of greater quantities of gasoline from each barrel of crude oil. Cracking stills became a reality. The new processes produced better fuels at lower costs. Such results flow from research, and we are only in the beginning.

One gains perspective as he considers the following statement made by Dr. Robert E. Burk, of the chemical research department of the Standard Oil Company, Ohio:

"While speaking of gasoline, I should like to say something on cracking and antiknocks. The work of William Burton and others on oil cracking and of the General Motors research staff and others on anti-knocks, has resulted in an average increase of some ten per cent in the power derived from a gallon of motor fuel at the present time and has about doubled the yield of gasoline from crude oil. This amounts to a gain of roughly a billion horsepower in this country alone. Now it seems that there is a remarkable river named the Tennessee which runs through Tennessee but drains all 48 states, a power which is derived from a body known as the Tennessee Valley Authority. Without attempting to weigh the price against the glory of this authority, I have added up the approximate horsepower in the contemplated electric installations of all the TVA dams that is, Wilson Dam, Norris Dam, Wheeler Dam, Pickwick Landing Dam, Gunterville Dam, and Chickamauga Dam, and the sum of all these monuments is about 715,400 horsepower. This is less than one tenth of one per cent of the horsepower gained from the anti-knock and cracking research. Moreover, I have never heard a single politician eulogize William Burton or the General Motors Corporation for their work in conservation. In any case, we shall plainly be dammed in a big way if politicians try to equal the power-conservation feats of the chemist by building the thousand odd TVA's which would be necessary."

Rapid developments in ferrous and nonferrous metallurgy have attended the evolution of the motorcar industry. Modern alloy steels have contributed to improved structures, reduced weights, increased power, and lower costs. The metallurgy of cutting edges has multiplied production and has contributed to revolutionary improvements in machine tools.

The motorcar industry has helped to bring many new industries into existence, and also has caused the output of many older industries to be multiplied. The list includes, among many others, iron and steel, fibers and fabrics, plate glass and plastics.

Examples of the great contributions that have been made to the people of the world through research by the industry could be recounted endlessly. Developments in commercial chemicals and dyes in the past 25 years have been prodigious. Great new industries have grown from research devoted to synthetic fibers—rayon and nylon. Volumes have been written about research in plastics and their commercial possibilities.

Research in the fields of radio and electronics already is bringing about revolutionary changes in our lives and has contributed vitally important instruments to our prosecution of the war. David Sarnoff, president of Radio Corporation of America, said in a recent address:

"It is radio which has made possible a war of speed and mobility on land, at sea, and in the air. Bombers fly to their targets and return to their bases with the aid of new radio devices. Radio electronic sentinels stand watch on shipboard and along the coast. Infantry, artillery, and tank units co-ordinate their movements by radio. The United States now has fighting forces stationed

more than 60 strategic locations on the world map. Its Navy operates on the Seven Seas. Without instant reliable radio communication it would be impossible for these widespread forces to function as a unified war machine."

He spoke of the great new areas opened to science by the electron microscope with its range of 100,000 diameters, the spectacular new industrial processes which stem from applications of electron tubes, and nationwide television as an early postwar probability. He concluded by saying:

"I have mentioned only a few of the promises of the future. There are many more. In each of them, science has written a promissory note, payable when the war is ended in terms of a fascinating new civilization in which life will be easier and more abundant, transportation swifter and more comfortable, and communication by land and sight a universal convenience."

Research is an important means of conserving our resources and insuring the future of America. F. Russell Michowsky, research engineer, says in the preface to his booklet, "Industrial Research:"

"There are no new lands for America to exploit. It is probable that there are but few new mines and oil deposits yet to discover. There is left but one possible source of new wealth to replace the wealth lost in war. This source of wealth is the discovery of new products to manufacture and sell. It is on this source of wealth that we must depend now and in the future for the means to maintain and raise our standards of living.

It is from the research laboratory that this new wealth must arise, which has originated in the past the new wealth represented by the automobile industry; the radio industry; and the industries founded in the movies, the electric lamp, the aeroplane, plastics, rayon, nylon, Kodak, and hundreds of other new products. This wealth has never been fairly estimated but it probably represents well over two hundred billion dollars."

Equally entrancing vistas are opened to our view when we hear physicists, electrical scientists, chemists, medical-research men, refrigeration and air-conditioning researchers tell of the things that lie ahead. During the quarter century just passed, research has brought important new means of refrigeration to the people of the world, and, as usual, people of the United States have been the major beneficiaries. For a long time we have taken abundant food supply as a matter of course—something like the air we breathe—that just happens. Reports of famine in other countries have left us almost untouched. Only recently have we heard of "food shortages" and "food rationing;" of these matters we shall hear far more in the months to come. New importance now attaches to food production, food preservation, food preparation.

In this country more than 17,000,000 gas and electric automatic refrigerators, installed in American homes, conserve our food supplies. This great battery of food preservers is augmented by great cold-storage warehouses, by refrigerated freight cars, and by refrigerated ships, by frozen food lockers and by commercial plants for processing frozen foods. As we look forward to the post-war days we realize that this art of controlling temperatures at subnormal levels is only in its beginning, and that new conveniences and new means of conservation will help to give increased employment to the workers of America and new services to American homes.

Air conditioning is only in its swaddling clothes; future homes, particularly in our own blessed land, will be maintained at constant comfort levels through out the year. Summer air conditioning will be no more unusual than

central heating and modern plumbing. Already our engineers have installed residential all-year air-conditioning plants from the Atlantic to the Pacific and New England to New Orleans. These plants bring about both summer cooling and winter heating from the same gas flame. Only the removal of war's restrictions is required to make such plants as readily available as modern gas-heating plants.

Aircraft technology has reached a tempo without precedent under war pressures. To visualize the revolutionary effect of air transport one need only read editorial and advertising matter in our current magazines. That our minds fail to grasp the third-dimensional implications that characterize air transportation, is made clear when one studies current controversies about "freedom of the air."

Yes, warfare forces technology to adopt a faster pace. After World War I many existing industries were greatly accelerated, and great new industries came into existence. When the curtains which now, of necessity, conceal the work being done in our research laboratories, are withdrawn, many essential "samples" for developing new industries and accelerating older industries will be disclosed.

Can "we, the people" insure a favorable environment for the full development and the maximum duplication of these "samples?" We can if we will, but rigorous thinking and decisive action are needed—not tomorrow—but today. "It is later than we think."

RESEARCH METHODS IN POLITICAL ECONOMY

A profound and terribly disquieting change has taken place. Our people are increasingly willing to exchange freedom of opportunity for empty promises of security. So far this country has been too strong and too rich to be overthrown by revolutionary socialism. Nevertheless, we are the victims of insidious, encroaching socialism. We may as well face that fact and the corollary fact that, in the degree to which socialism, paternalistic government, and dictatorship advance, freedom of opportunity diminishes.

As we consider the current scene, we must avoid confusing symptoms with the underlying disease. Corruption of the courts, the ascendancy of demagogues and crackpots, the expansion of bureaucracy with its vagaries and stupidities, dictatorship are among the *symptoms* of national decadence. The psychological basis of our retrogression is clearly analyzed and projected by Henry C. Link in "The Rediscovery of Man:" "After centuries of painful progress toward freedom and democracy, the world is rapidly moving back into social slavery . . . Such slavery does not just happen. It must be deserved . . . In the United States, which is moving in the same general direction, we can still observe the process by which the people are being prepared."

In a book, entitled "Human Engineering or the Mankind of Humanity," written by Korzybski some years ago, it was pointed out that, whereas some human activities are based upon scientific method and thinking—"rigorous thinking" Korzybski called it—many other human activities stem from unscientific traditional thinking, or "speculative philosophy."

Korzybski developed the theme that activities growing out of scientific thinking and method tend to advance geometrically, whereas activities based upon traditional

thinking, like political economy and jurisprudence, advance only in arithmetic ratio. From this hypothesis he developed the thought that lack of understanding and conflicts develop because the rapid advance of scientifically generated projects outdistances advances in traditional fields with a consequent strain upon the social structure. Having learned to apply the methods of scientific research successfully in so many fields of human endeavor, why should we not use similar methods to accelerate advancement in other fields equally important to human welfare?

What of taxation, for example? Someone recently said that if one of Hitler's cleverest agents had devised the Federal taxes of the United States solely for the purpose of accomplishing Hitler's aims he could have done nothing more effective than has already been done by our own legislators.

In the spring of 1939 I had the privilege of addressing the Congressional delegation from Indiana on the subject of "Business Taxes," and I presented this thought, which was not new. I quote from the *Congressional Record*:

"A final suggestion for long-range planning is made which may be too idealistic for realization. Would it not be a measure of constructive statesmanship to place tax planning and specific recommendations in tax matters to the Congress within the control of a well qualified permanent nonpartisan board, which would approach our present confused inefficient self-defeating aggregation of tax measures with an objective long-range constructive viewpoint, calculated gradually to bring order out of chaos and to develop a carefully correlated tax program, scientifically planned to produce maximum revenue and to avoid undue restriction of those activities which are essential to develop increasing national income?"

In the third supplement to *Fortune* of December 1942, the following significant comments on taxes are found:

"In the final analysis, it is the elusive giant, confidence, that chiefly influences, if it does not control, the birth rate and expansion rate of business . . . No policy is potentially more dangerous for economic life or death than taxation."

Then follows this suggestion:

"But when the first big postwar tax bills are written, piecemeal reforms will not suffice to serve the needs of an expanding economy. What will be needed is a complete and uninhibited overhaul of the whole structure, starting from the basic question of what a federal tax system is for. To this end a nonpartisan commission of experts, both government and private, should be set up, along the lines of a British Royal Commission or our own Baruch Rubber Committee. Its personnel should command general confidence, so that its report and recommendations will have weight with Congress. It should start with the assumption that we have no federal tax system at all, and then lay down the lines along which a good one must be drawn. In addition, as proposed in a resolution offered by Representative Coffee (Washington), the Commission should study state and local tax systems, seeking ways to integrate all three."

The importance of such procedure with respect to taxes, which at best must continue for many years at extremely high levels and which for that reason, if for no other, should be planned so as to produce *maximum revenues* with the least restrictive effect upon *tax sources*, is underlined by the vast confusion and delay that have attended recent deliberations and controversies in tax matters between the Congress and the Administration.

In the less complex but much debated field of patent practices, President Roosevelt has established a healthy precedent which may have far-reaching effect in our political economy. A distinguished "nonpartisan group

of experts, both Government and private," was organized in 1941. The National Patent Planning Commission is headed by Charles F. Kettering, and includes Chester Davis, president of the Federal Reserve Bank of St. Louis; Francis P. Gaines, president of Washington and Lee University; Edward F. Grady, consultant to the Undersecretary of War; and Owen D. Young of the General Electric Company. A. A. Potter, dean of engineering, Purdue University, is executive director of the Commission. The Commission, in conjunction with the Department of Commerce, is authorized to "conduct a comprehensive survey and study of the American patent system and consider whether the system now provides the maximum service in stimulating the inventive genius of our people in evolving inventions and in furthering their prompt utilization for the public good." Here, indeed, is a group to "command general confidence, so that its report and recommendations will have weight with Congress."

The Commission's first report was made last June. After face-to-face discussion of its recommendations by the Commission with President Roosevelt, legislation was prepared embodying the Commission's recommendations. In contrast to the political persiflage presented to the Senate patent committee by various "speculative philosophers" is the Commission's recommendation that "It would not be advantageous to incorporate compulsory licensing in our patent laws." Without equivocation the Commission's report states that "The strongest industrial nations have the most effective patent systems, and, after careful consideration, the Commission has reached the conclusion that the American system is the best in the world."

The National Patent Planning Commission is an encouraging example of application of the scientific method to affairs of government. The method of approach used and the recommendations made by this Commission afford a startling contrast to the provisions of the Kilgore Bill, which is symptomatic of the worst tendencies of our times. The Patent Commission is quite conscious of the profound and beneficial influence of the existing American patent system upon our national welfare, proposes to retain its body of sound precepts and practices, and suggests legislation which will remedy its deficiencies and increase its scope of service. Proponents of the Kilgore Bill, at the other extreme, disregard all historical facts with respect to research and patents; set forth certain untrue and indefensible promises; and propose socialization, elaborate bureaucratic control, and destruction of existing incentives with respect to research and patents.

Walter Landis, vice president of the American Cyanamid Company, discusses the Kilgore Bill and its implications at length in a well-documented brochure dated October 15, 1943. Vannevar Bush's letter to Senator Kilgore,² and Frank B. Jewett's address, "The Promise of Technology,"³ also deal with this subject.

Liquidating billions of dollars worth of war contracts quickly and equitably to the end that reconversion of and re-employment by an expanding peacetime industry may not be delayed unduly is another important task for a well-qualified commission. Restoring the flow of capital which long ago ceased to be available in sufficient volume to provide for an expanding economy is another problem which must be solved if America is to continue its forward march toward full employment and an economy of plenty.

Here also is an opportunity to use the nonpartisan fact-finding technique applied by men whose abilities and reputations are above question. The research division of the Committee for Economic Development may be expected to contribute to the solution of these and kindred problems of magnitude beyond all earlier experience, but of importance so vital that we dare not delay aggressive and comprehensive approach to their solutions.

The Administration has established significant precedents in the Baruch Committee report on rubber and in the Patent Planning Commission. Business leadership is using sound research techniques in the operations of the Committee for Economic Development, and in those of many other groups who recognize and propose to deal realistically with postwar problems. All thinking people of the United States must support the application of the research method to vitally important problems where scientific approach heretofore has been notably lacking.

QUO VADIS?

The people of the United States have received incalculable material benefits from research which is indigenous to the fertile soil of American free enterprise. Our generation now witnesses the dangerous erosion of that soil and rapid depletion of its fertility. To win this greatest of all wars after paying the hideous price in terms of life, human wreckage, natural resources, and other forms

of material wealth and then to lose the fundamental freedom of opportunity would be a terrible tragedy. The human race, despite its consistently suicidal proclivities so far has been preserved by the operation of immutable laws which were established in the beginning by the Designer of the Universe. If such laws were amenable to modification or repeal, our remote ancestors would have "perished from the earth" long before Americans engaged in experimentation with "government of the people, by the people, for the people."

The tragic loss of fundamental freedom may be postponed by the operation of the immutable law of action and reaction, but the nation can be made permanently safe only by the redirected effective education of its people in the fundamental ideals upon which our culture has been built. As a reunited people we must experience a rebirth of the integrity, the moral and spiritual values, and the willingness to participate in government that inspired and animated the founding fathers.

"It is later than we think."

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Radio in Aviation

CHARLES I. STANTON

RADIO and communications occupy an increasingly important role in all considerations of postwar flying problems. The development of low-cost aircraft radio equipment is vital to the growth of private flying, but radio and communications are particularly crucial to commercial aviation. In fact, satisfactory control of the increased commercial traffic expected after the war will be impossible without improved radio and communications equipment. The alternative would seem to be to reschedule air-carrier traffic in the interest of safety, and, indeed, this has been done to a limited extent at times.

The magnitude of this problem can be appreciated when it is realized that aircraft movements handled by Civil Aeronautics Administration traffic-control centers increased from about 25,000 a month in 1938 to more than a million a month in 1943, a 40-fold increase in five years. Part of this increase resulted from the creation of 15 additional control centers, but with 23 now in operation the United States is believed to be divided into the smallest areas practicable for handling traffic which

A pioneer in the application of radio to aviation and long closely concerned with radio as a factor in building and operating airways in the United States, the author reviews the latest applications of radio to the operation of commercial air lines in this article, and predicts a great need for low-cost radio equipment in the many privately operated airplanes that may be expected in postwar years.

moves, usually, at about 180 miles an hour. Nevertheless, every indication points to a further increase. This increase was foreseen during the years just before the war, and several steps were initiated to take care of it, but war-dictated priorities halted action on many of the plans.

IMPROVEMENTS IN RADIO RANGES

In 1941 there was begun what was intended to be a five-year program for shifting radio ranges over to ultra-high frequency. The principal limitations upon the use of the present type of range are: crowded condition of the 200- to 400-kilocycle frequency band; susceptibility of the stations operating on frequencies in this band to interference over long distances; night effect or signal distortions resulting from reflections from the ionosphere; vagaries resulting from distortion of the radiation pattern by the effect of irregular terrain; high degree of interference from atmospheric static; and precipitation static.

Essential substance of an address presented before the communication group of the AIEE New York Section at a joint meeting of the Section and the New York section of the Institute of Radio Engineers in New York, N. Y., February 24, 1944.

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Present radio-range frequency assignments are spaced only three kilocycles apart, and it is necessary to operate a number of stations on each available frequency, relying upon geographical separation to limit interference. A saturation point has already been reached, and few if any low frequencies are available for future expansion of the range system.

To overcome the limitations of the low-frequency ranges and provide for future expansion of the airways system, the CAA for several years has been engaged in the development of an ultrahigh-frequency radio range to operate in the frequency band from 119 to 126 megacycles. At these frequencies, interference from atmospheric and precipitation static is practically nonexistent, and interference between stations on the same frequency will not occur, at practical flying altitudes, provided their geographical separation is 200 miles or more.

The ultrahigh-frequency range developed by the CAA operates on a somewhat different principle from the low-frequency ranges, and provides one pair of courses indicated visually in the aircraft by a zero-center left-right indicator; and another pair of courses at right angles to the visual courses, which are indicated by interlocked keying of the Morse code characters D and U (dah dit dit and dit dit dah, respectively) with 1,020-cycle audio tone modulation.

The antenna system of the ultrahigh-frequency range is in general similar to that of the low-frequency range except that its physical size is very much smaller while the electrical spacing of the radiating elements in terms of the operating wave length is very much greater. The five radiating elements may be either horizontal loops or vertical rods, depending upon whether horizontal or vertical polarization is desired. One pair of diagonally opposite corner radiators and the center radiator constitute a complete two-course range antenna, so that the two pairs of diagonally opposite radiators form two two-course range antenna systems independent of each other except for the common center element. The antennas of the pair radiating the signals that register on the visual indicator are excited 180 degrees out of phase by side-band energy arising from modulation of the carrier frequency by 90 cycles and 150 cycles simultaneously, but from which the carrier frequency itself has been suppressed. The center element radiates the carrier frequency plus also 90-cycle and 150-cycle side bands. The side-band energy radiated from the center element combines vectorially with the radiation from the corner elements to produce a field pattern resembling two cardioids with axes extending in opposite directions along the line of radiators, and two points of intersection directly at right angles to the line of radiators. In one of these cardioid patterns the 90-cycle modulation predominates, in the other the 150-cycle modulation, while at the points of intersection both modulations are equal. Thus, the line of intersections defines a course with modulation at 90 cycles greater on the one side and with modulation at 150 cycles greater on the other side.

The other pair of radiators produces aural courses at right angles to the visual courses in exactly the same way, except that a single modulation-tone frequency, 1,020 cycles, is used and the courses are defined by keying a D (dah dit dit) into one cardioid and a U (dit dit dah) into the other. The center antenna common to both systems must radiate the carrier frequency and

all of the side bands required to produce the desired directional patterns in combination with the radiation from the corner antennas.

The aircraft receiver for use with the ultrahigh-frequency range is of conventional design. It has two independent output circuits: one for the frequencies of 90 and 150 cycles which actuate the visual meter, and the other for the tone frequency and speech. The 90- and 150-cycle frequencies are separated by two band-pass filters. The outputs of the filter sections are rectified, and the resulting direct voltages are applied in opposition to the zero-center meter so that it deflects to one side or the other depending upon whether the 90-cycle or 150-cycle signal is the stronger.

The two-course-aural and two-course-visual range system has a number of important advantages over the four-course aural range in addition to those already cited. In the four-course range, the same "off course" signal is heard in two opposite quadrants. When a pilot is completely lost and must rely upon a four-course range for orientation, it may be a tedious and time-consuming process to determine which of two quadrants he is in. The two-course-aural and the two-course-visual range, on the other hand, has no quadrant ambiguity, since its courses are formed by four unidirectional patterns rather than two bidirectional patterns. In this, too, the course indications are produced by varying modulation levels in the field about the station while the carrier itself is radiated in a circular pattern and does not vary with azimuth. It is thus possible to use automatic volume control in the aircraft receiver to eliminate or reduce fading and surges in the signal level over rough terrain without affecting the definition of the courses.

Ultrahigh frequency ranges were satisfactorily serviced on the Chicago-New York airway in 1941, but entry into war made it impossible to proceed with plans to convert the entire airways system. In fact, about 15 per cent of the ranges of the existing type had to be removed from domestic service and installed elsewhere for use of the military air forces. The range equipment at Evansville, Ind., for example, was relocated on Ascension Island, to guide fliers across the South Atlantic.

OTHER ULTRAHIGH-FREQUENCY APPLICATIONS

Ultrahigh frequencies will have other applications in the airway system. Airport traffic-control towers will operate in this band, as will the instrument landing system at airports.

The CAA, in co-operation with the War Department, is installing at more than 100 airports ultrahigh-frequency radio transmitting equipment designed to permit properly equipped aircraft to make instrument approaches in very low ceilings and visibilities—or even landings in conditions of zero ceiling and visibility. At present, only military aircraft are so equipped.

A complete instrument landing system consists essentially of four separate transmitting stations located on or near the airport. These four elements are known as (1) the localizer, (2) the glide path, (3) the boundary marker, and (4) the outer marker. A middle marker is being installed at some airports. Although any number of markers may be used, two are usually sufficient.

The localizer provides a very accurate lateral guidance so that approaching aircraft can maintain a heading that will lead them over the center of the runway. The glide

path provides vertical guidance enabling the aircraft to maintain the proper rate of descent. The markers provide reference points or "fixes" along the approach paths, which permit pilots to verify their positions and altitudes.

No glide path is included in current installations because equipment is not available, but equipment is expected to be installed as soon as it is available.

Use of the localizer and markers alone permits instrument approaches under weather conditions much less favorable than those now required. Thus, approaches to an airport with 100-foot ceiling and one-fourth-mile visibility will become feasible, whereas present minimums are 400-foot ceiling and one-mile visibility.

The localizer is basically a two-course radio range operating at ultrahigh frequencies. A linear array of horizontal loops is placed at right angles to the axis of the runway and radiates what amounts to two space patterns. These patterns represent modulation of the same carrier at 90 cycles and at 150 cycles. The signals are rectified and separated in the aircraft receiver, and the two resulting direct voltages are applied to a right-left indicator which indicates the difference between these voltages. The two patterns cross only at the two points where the two signals are equal in amplitude.

Along these two directions, which are 180 degrees apart, the indicator shows zero or "on-course." Along any other direction the amplitudes of the patterns are different and the needle moves to the right or left, depending upon which of the two signals predominates. The rate at which the ratio of the amplitudes of the two patterns departs from unity, as the azimuth changes from "on-course," determines the so-called "sharpness" of the course.

The aircraft receiving apparatus consists of a small marker receiver and a localizer receiver. The output of the former is fed into three filters, each of which controls a pilot light. Thus, if the modulation happens to be 400 cycles the corresponding filter functions to close the power circuit to its pilot light. By this means the pilot knows which marker is being received.

To receive the horizontally polarized localizer signal, either a horizontal loop or a horizontal receiving antenna is placed on the airplane above the fuselage. The latter is a pair of elements approximately one-fourth wave length long, grounded at the junction point. The line is tapped on either side of this junction to obtain an approximate match of impedances.

AIR TRAFFIC CONTROL

Ultrahigh-frequency radio ranges, airport-control-tower communications, and instrument landing systems are only a part of the answer to postwar traffic increases. Air traffic control already has been discussed in a previous article (*EE, April '44, pp. 119-25*).

One bottleneck in the air-traffic-control system is the means of posting flight information at the centers. At present, data concerning the progress of each plane are written on slips of paper and placed in slots on a board, an entirely manual operation. It is slow at best, and when traffic is heavy, the job of posting the slips causes the board to be obscured too large a portion of the time.

Introduction at the earliest possible moment of electrically operated boards, on which flight data are posted automatically, is proposed. This plan has been tried successfully at Washington National Airport and will be

installed in the busiest centers as soon as funds are made available and the equipment produced.

Although there has been a forced wait for improved equipment, the war has not slowed down attempts to improve procedures. Approach control is one of the more important innovations being developed. Up to now it has been customary for a plane approaching an airport to maintain contact with the control tower only indirectly, through an airline or military radio station, becoming subject to airport-tower control only when it came in sight of the field. Under the approach control system, the controller takes over when the plane comes within 15 miles. This makes possible landings only 5 minutes apart in instrument-approach weather, as compared with 15-minute separation under conventional methods. This system is in operation at Atlanta, Ga., Kansas City, Mo., and San Diego, Calif., and is being extended as rapidly as possible, subject to the approval of the chief users of each airport.

PRIVATE PLANES FOR POSTWAR FLYING

Thus far radio and communications have been discussed primarily as they affect commercial air transportation. Today, of course, commercial and military planes are the chief users of these facilities. In the postwar decade, however, there may be as many as 500,000 civil airplanes in the United States, most of them privately owned; it is inevitable that many of these will be equipped with radio.

First, the private flier will want radio to make his flying simpler and safer. The radio compass, which makes it possible for a plane to fly straight toward the station to which it is tuned, will probably be standard factory equipment, except on the lowest-priced planes and on training planes that stay near the airports on which they are based. Experienced pilots all know how easy it is for beginners to get lost in the air, and radio can be the most valuable of all flying aids, both to the new as well as the veteran pilot.

Perhaps most important, the private flier will need and demand radio for his use in obtaining weather information. There can be no safety in widespread private flying without rapid transmission of weather information to planes in flight. Hence the private owner's radio equipment probably will be a receiver operating on ultrahigh frequencies, with a direction-finding attachment. In quantity production, such equipment should sell for a modest price. At least one company is prepared to produce the receiver alone for less than \$30. For communication, many private owners will want a transmitter operating on a high frequency for communication with airport towers and CAA stations. This transmitter should cost not more than \$50 on a mass-production basis, and a complete installation might cost \$150 on the same basis.

This article has been confined to the radio and electrical developments in prospect for aviation during the immediate future. These, of course, are mild in comparison to what may be expected when the electronic devices being used in this war are adapted to peace-time needs. But that will involve a long-range program of development, and will not, as many laymen believe, happen overnight. The CAA hopes to work on this, in co-operation with the research departments of private industry and universities, as soon as war conditions permit. In the meantime, however, effort is being concentrated on solving today's problems with today's means.

Electrical Engineering in the Postwar World

II—Position of the Engineer

EVERETT S. LEE
FELLOW AIEE

TODAY the engineer is working under enormous pressure due to the keenness of the competition of the war, competition the like of which there has never been before. The war production is everywhere requiring his services. As he solves urgent needs, newer needs come into being for solution. On the day the war ends, the engineer will be on the firing line of engineering contribution for war. And the day after the war ends, he will be on the firing line of engineering contribution for peace.

One thing is certain in the postwar world—the engineer will continue in his present role to unearth new knowledge and to produce new things. And by engineer, I mean scientist and engineer. Also, the engineer will continue in his present role to improve present things. These characteristics define the engineer.

Everything we have comes to us from the engineer. This paper from which you are reading, the press on which it was printed, the transportation which brought it, all came to us from the engineer. The house in which you are, the furnishings, the lights, the street outside, the bridges, the tunnels, the buildings of the city, the telephones, the telegraph, the movies, have all come to us from the engineer. The farm equipment on the farms, the roads, the automobile, the radio, the airplane, electric power for the home, electric power for industry, the processes of industry, the metals from the mines, have all come to us from the engineer. The tanks, guns, planes, ships, and ammunition of our present war production have all been brought into being by the engineer.

The opportunities for all people to work have come to us from the engineer. The opportunities for all people to work in the future will come to us from the engineer.

The engineer works. He works to bring new things into existence. He works to bring into being the first of all of the things which we have. He works to fashion

them into useful articles. He works together with all working men and women of the land. And he lives with them in appreciation of their contributions and his dependence upon them as they have dependence upon him.

At the same time, in his daily work, the engineer is an individualist. His workshop is nature. His stock in trade is nature's laws. His tools are the sciences. His output is the first one of new things. He gives guidance to the continued fashioning of things by millions and millions of other workers. In this he provides for all the jobs there are. He lives in a world of scientific freedom limited only by his ability. He serves with other engineers, often times with many, yet he retains his individualism in engineering contribution.

This is the engineer as he has been, is, and will be. Recently newspapers published the account of the death of Leo Hendrick Baekeland, chemist and chemical engineer. He invented

Velox in 1899; picture to yourself the extent of the photographic industry into the manifold walks of life. He invented bakelite in 1906; today plastics is still a magic word as it includes items by the thousands "from billiard balls, fountain pens, umbrella handles, buttons and pipe stems to airplane propellers, automobile self-starters, telephone receivers, and switchboards and insulation for battleships." (New York *Herald Tribune*, February 24, 1944). Or recall the

engineering contributions of Edison, of Steinmetz, of Westinghouse, of Goethals, of Hammond, of McNaughton, and of a host of others that you know, and if the complete record of all engineers could be written, it would be a record of services rendered to their fellowmen by thousands and thousands and thousands of engineers, all to the end

This article, second in a series discussing the general subject, is devoted to determining the probable part the engineer will play in the postwar world. As in the past, the engineer is expected to expand and apply knowledge for the benefit of all. Beyond this, however, is the question of the control by the engineer of the uses to which his products may be put, in order to insure that they are used for good and not for evil. Because of his knowledge, professional position, and the strength of engineering societies, the engineer should take an active part in guidance toward a wholesome life.

An address presented at a conference on "The Engineer in the Postwar World" on March 4, 1944, in New York, N. Y., under sponsorship of the Research Bureau for Postwar Economics and its co-operating institutions.

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that all men would have available for their use the manifold wonders of nature.

SIGNIFICANT CONTRIBUTIONS OF ENGINEERING

Most significant to our way of life has been the providence of the fruition of engineering contributions in these latter days. When a reflected radio signal was first observed in the United States Naval Research Laboratory some years ago, engineering and scientific skill, ability, perseverance, and hard work put together with engineering ability in other fields enabled the British later to put up a protective curtain to keep the enemy from Britain after he had overrun France, producing a power which preserved the very principles which were its foundation. May there be a recognition of this fact.

Or, when several years ago Russia came to American industry to obtain American engineering understanding and technique, the engineering books of industry were opened to the Russians, engineering knowledge was imparted, engineering know-how was provided in person in Russia by Hugh Cooper and many others, and today the result of that imparted and inspired engineering ability propelled by intense application, perseverance, and hard work by the Russians has built up again a power which has preserved the very principles which were its foundation. May there be a recognition of this fact.

Or, when Marvin Camras, young engineering student at the Armour Institute of Technology just a few years ago, brought to the science of recording sound on wire a new concept to give greater fidelity and which has since enabled information of the enemy to be recorded from the air for the services, here was a classic example of a young man on the firing line of engineering knowledge, driving of his ability to produce a new and useful result, typical of what is going on in the lives of thousands of our young engineers who are today contributing in their early years to engineering and scientific advance as no one else can do. In our young engineering manhood our future is secure that there will be continued contribution just as it always has been and just as it always will be. May there be a recognition of this fact.

The position of this young engineering manhood is being sacrificed however. War is ruthless. When the President of the United States called upon us all to make our country an arsenal of democracy, there was immediate action and we witnessed the acceleration into being of the greatest production output the world has known and in the shortest time. The basis of this was the engineer. As the engineer had permeated the production for peace, so he permeated the production for war. And the source of this engineering bulwark was the young engineers trained in the colleges of our land and entering the profession each year at the increasing rate necessary to maintain the engineering output required by our country in time of peace. This annual inflow to American engineering talent, ability, and understanding had grown to 15,000 engineering graduates in each year. Today the number available to American engineering outside of the services is practically zero.

As the engineer faces this situation which has been forced upon him even as he pleaded against it, we can only trust that the sacrifice which has had to be made is recognized by those in high places that it will not have to be extended and that just as soon as possible the lost ground can be regained.

The position of the engineer in the postwar world is secure as regards the fact that he will continue to produce. But the larger question is, what will the people do with the products of the engineer? What the engineer produces can be used for good or for evil. If he, fearing its use for evil, does not produce it, neither is it available for good. Thus he produces it, and the people who use it must learn to use it for good. The motives of the engineer are for good, for to use the laws of nature he must be honest and in using the laws of nature he just naturally is honest. And he expects honesty in the use of his products. And where there is not honesty, there will be travail.

As the engineer has worked he has associated himself with other engineers of his calling to build the professional engineering societies of the land—active, virile organizations of strength where together with his fellow engineers he may present to the world the record of what he has accomplished. And as these societies have grown in their individual strength, the profession has come into being. They are the profession.

In the engineering societies are engineers from every abode of engineering endeavor—from every industry in the land; from the large company; from the small company; from every utility; from the transportation systems of the country; from the schools and colleges; from government, municipal, state, national; from private practice; from the countries of the world; from everywhere.

And in these places of engineering accomplishment the engineer is found in every position. There are the young college graduates entering the profession to accept their initial responsibilities, the junior engineers active and progressive, the senior engineers of experience, the chief engineer, the president, the chairman of the board. In every place of life the engineer will be found, and his contribution to society thus goes beyond the technical into the administrative with broad responsibilities for human welfare. And these have been reflected in his professional society life.

There is the urge to make these even more prominent. Some 11 years ago there was founded the Engineers' Council for Professional Development to co-ordinate and promote efforts to attain high professional standards of education and practice, greater solidarity of the engineering profession, and greater effectiveness in dealing with technical, economic, and social problems. Much for good has been accomplished. There is still much to be done.

But by and large the engineer's contributions are to the technical, and from these there has resulted a massive monument of accomplishment; a foundation, structure, and superstructure of achievement; a wealth of things for the people to use. To this picture we return again and again; it is so prominent.

And as we consider it, we see most prominently displayed an equal picture as we look into the postwar world with all the peoples of the world producing and wanting and needing these things. What the engineer would accomplish in the solution of his problems beyond the technical, so the world would accomplish in keeping the peace for which so great a struggle is now in progress. The two are much the same, practically identical.

With all the planning of the present time for the postwar world, in whatever phase, there is recognition that where war is tangible in objective, peace is intangible in objective; therefore much more difficult to progress. But the underlying laws are easy—everybody knows them. Do unto others as ye would be done unto you. Love thy neighbor as thyself. Love thy God with all thy heart. These do and thou shalt live. Herein is the opportunity for a wholesome living. That is what each man wants. That is what each man shall have if we have peace.

But the ramifications are enormous, the complexities are intense, and in spite of all controls power becomes amassed and conflict follows.

To the end that the individual engineer may contribute in the place where he is, the Engineers' Council for Professional Development has issued the pamphlet "Will You Help?" This calls upon all members of the local chapters, sections, and branches of the participating bodies, together with other local engineering organizations and interested groups, to participate in the co-ordinated societies' endeavors. Where this will lead will depend upon the activity of the groups and the earnestness with which they enter into the problems which they find. But potentially there is an opportunity to bring into discussion and suggestion for solution any problem suggested. Here is an opportunity for a portion of the engineer's time to be given actively to the solution of those problems which he wants to be solved and which must be solved to maintain the wholesome life. That this is not entirely new we recognize; that there is in-

initely more opportunity for great good, however, is clear. May the engineering profession see it clearly and progress it wisely.

The world today has plenty of opportunity to see and feel sacrifice. It is everywhere. And to what avail? That there will be brotherhood. To have brotherhood men must feel it, men must think it, men must act it. There must be a recognition of the love of God for man, of man for man, of man for God. Without this the position of the engineer in the postwar world will be insecure just as will be the position of his fellowmen. This is inescapable.

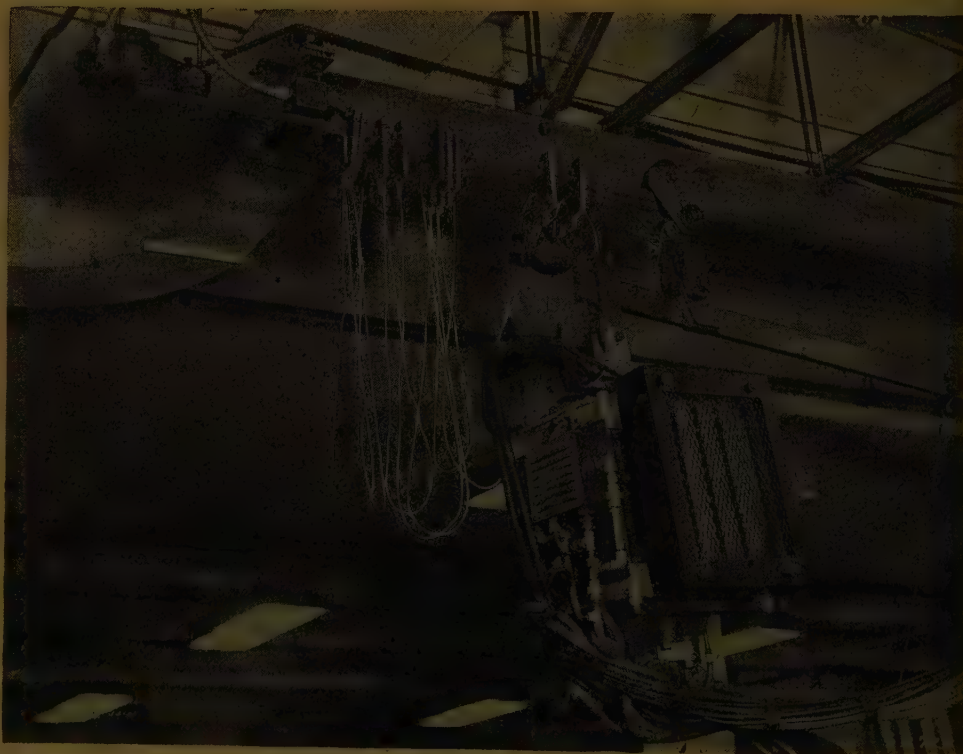
The engineer through his knowledge of nature's laws has the best of opportunity to contribute wise counsel. He knows that abundance must be paid for at great price. He knows there must be balances. He knows there must be safety factors. He knows you can't get something for nothing. He knows the havoc of uncontrolled power. He knows of the evil results of small squeaks.

Those and others the engineer can bring to the local discussion, and from the local to the national, and from the national to the international. It is most worthwhile.

And thus the engineer in the post-war world, continuing his contribution to the providing of things for the needs and welfare of the people, can bring to his locality and beyond the helpfulness of his understanding towards a wholesome life. The potentialities are enormous; the objectives make the effort worthy; the consequences of nonparticipation, which may even mean a recurrence of conflict, are just too serious to be allowed.

Overhead Welder Travels Assembly Line

This portable spot welder has halved the time and the number of operations necessary for assembling B-26 bomb-bay doors by the Glenn L. Martin Company. The skin, frames, and stiffeners for the doors are assembled in a fixture to be tack-welded with the portable spot welder and the entire assembly then is carried to a floor-type spot welder. The portable welder consists of a spot weld machine and transformer counterbalanced on a small beam pivoting from an overhead trolley which travels along a 50-foot I beam. The trolley is propelled by sprocket and chain powered by a one-third-horsepower electric motor. A 200-kva welding machine with a capacity of two thicknesses of 0.040-inch aluminum is used.



INSTITUTE ACTIVITIES

Summer Technical Meeting Program to Be Largest in the History of the Institute

The tentative program arranged for the AIEE summer technical meeting to be held in St. Louis, Mo., June 26-30, 1944, will be the largest technical program in the history of the Institute. This makes the meeting a fitting occasion to commemorate three important anniversaries in the electrical field—the 60th anniversary of the AIEE, the 100th anniversary of the Morse telegraph, and the 40th anniversary of the International Electrical Congress, which met in St. Louis in 1904. The program is comprised of approximately 89 technical papers and 31 conference papers to be presented in 28 technical sessions and conferences, in almost as many specialized fields of activity. The 28 sessions and conferences are in addition to the annual meeting, which will take place Monday morning, June 26; the conference of officers, delegates, and members, which will be held Monday and Tuesday afternoons; and the general session on Wednesday morning. Meeting headquarters will be in the Hotel Jefferson, which has good facilities with some air-conditioned meeting rooms.

JOINT LUNCHEON MEETING

Tuesday noon a joint luncheon with the St. Louis Electrical Board of Trade has been arranged. The luncheon meeting will be addressed by Lieutenant Colonel T. B. Holliday, U. S. Army Air Forces, Matériel Command, Wright Field, Dayton, Ohio. Colonel Holliday's close connection with the development of electric systems for aircraft places him in a position to give a talk of unusual interest, which will be supplemented

by an exhibit of equipment. He also is chairman of the Institute's committee on air transportation.

TECHNICAL SESSIONS AND CONFERENCES

Four sessions on electric equipment for military aircraft will present a variety of papers on generator control, relays, fuses, connectors, generators and electrical instruments, as well as aircraft lighting. Other sessions closely related to the war effort will deal with electric welding, industrial-power applications, electrochemistry and electrometallurgy, industrial control, and quality control by statistical methods as applied to manufacturing. The expanded program will present subjects such as industrial control, induction heating, marine transportation, electronic applications, and electric house heating, which are relatively new fields of activity. In addition, there will be sessions in the central-station field, which will treat the subjects of power generation, transmission, cables, switchgear, and relays, as related to wartime conditions.

To commemorate the Morse telegraph centennial a symposium of papers has been arranged which will review the state of the art of telegraphy after 100 years from several points of view.

HOTEL RESERVATIONS

The hotel committee has reserved accommodations which expire on June 15, at the Hotel Jefferson, headquarters, as well as at the Statler, Mayfair, Lennox, Mark Twain, DeSoto, Coronado, Park Plaza, and Claridge. Everyone expecting to attend the

meeting should have filled out and mailed the hotel reservation card, indicating his first and second choices of hotels, addressed to Russell G. Meyerand, chairman of the hotel committee, 901 Syndicate Trust Building, St. Louis 1, Mo. These cards were sent to most of the membership with the mailed announcement of the meeting. The Jefferson will not accommodate everyone expected to attend the meeting, but good rapid transit facilities are available in St. Louis.

ADVANCE REGISTRATION

Members who will attend the meeting should have filled out and mailed in the advance registration card received with the mailed announcement. This will assist the committee in making arrangements and will help to avoid congestion on arrival at the registration desk.

COMMITTEES

Those making the arrangements of the meeting are B. D. Hull, *chairman*; I. T. Monseth, *vice-chairman*; L. L. Crump, *secretary-treasurer*; F. A. Cooper, Jr. (*chairman, St. Louis Section*). Subcommittee chairmen: C. B. Fall, *finance*; C. H. Kraft, *meetings and papers*; B. T. McCormick, *registration and information*; R. G. Meyerand, *hotels*; E. S. Rehagen, *hospitality*; Guy W. Thaxton, *transportation and trips*; L. F. Woolston, *publicity*.

Future AIEE Meetings

Summer Technical Meeting

St. Louis, Mo., June 26-30, 1944

Pacific Coast Technical Meeting

Los Angeles, Calif., Aug. 29-Sept. 1, 1944



Memorial Plaza, St. Louis, Mo., only a few blocks from the Jefferson Hotel, headquarters for the 1944 AIEE summer technical meeting. Clustered around a central park area are some of the newest and most highly prized edifices in the city. Near by are the city's new police headquarters and the Central Public Library

AIEE Summer Technical Meeting

● **ABSTRACTS** of most papers appear on pages 25-352 of this issue and pages 146-7 of the April 1944 issue.

● **PRICES** and instructions for procuring advance copies of these papers accompany the abstracts. Only numbered papers are available in pamphlet form.

Monday, June 26

9:30 a.m. Registration

10:00 a.m. Annual Meeting

President Nevin E. Funk, presiding

Address of welcome, William McClellan, AIEE Past President

Board of directors' report (in abstract), H. H. Henline, national secretary

National treasurer's report, W. I. Slichter

Committee of tellers' report on election of officers

Introduction of president-elect and presentation of president's badge; response by President-Elect, Charles A. Powell

Report on Institute prizes for papers, F. A. Cowan, chairman, committee on award of Institute prizes; presentation by President Nevin E. Funk

Presentation of Lamme Medal to Arthur H. Kehoe

Presentation of Faraday Medal of Institution of Electrical Engineers to Irving Langmuir

Any other business that may be presented

President's address, Nevin E. Funk

2:00 p.m. Conference of Officers, Delegates, and Members

Tuesday, June 27

9:30 a.m. Power Generation

44-98. THE SUMMATION OF LOAD CURVES. R. F. Hamilton, War Production Board

44-85. PREVENTION OF ROTOR-WINDING DEFORMATION ON TURBOGENERATORS. J. G. Noest, Consolidated Edison Company of New York, Inc.

44-106. THE EFFECT OF WEATHER ON THE SYSTEM LOAD. H. A. Dryar, Philadelphia Electric Company

44-107. CONDITIONS CONTROLLING THE ECONOMIC SELECTION OF PRIME MOVERS. B. G. A. Skrotzki, Consolidated Edison Company of New York, Inc.

CP.* PROGRESS REPORT ON TURBOGENERATOR STANDARDIZATION. AIEE group of AIEE-ASME Joint Committee on Turbogenerators

9:30 a.m. Aircraft Equipment

44-89. THE DIFFERENTIAL GENERATOR-CONTROL RELAY FOR D-C AIRCRAFT ELECTRIC SYSTEMS. F. E. Crever, General Electric Company

44-90. AIRCRAFT FUSES MUST PROTECT. J. G. Lebens, Jr., Bussmann Manufacturing Company

44-108. AN AIRCRAFT DIFFERENTIAL-VOLTAGE CUT-OUT. O. C. Walley, Westinghouse Electric and Manufacturing Company

44-88. A-C CONTACTORS FOR AIRCRAFT. F. J. Russell and A. P. Charbonneau, Cutler-Hammer, Inc.

9:30 a.m. Basic Sciences

44-95. FORMULAS FOR THE FOUR-TERMINAL-NETWORK PARAMETERS OF UNIFORM NETWORKS. W. R. LePage, The Johns Hopkins University

44-109. FORMULAS FOR CALCULATING SHORT-CIRCUIT FORCES BETWEEN CHANNELS LOCATED BACK TO BACK. T. J. Higgins, Illinois Institute of Technology

44-110. THE COMPUTATION OF MAGNETIC-FIELD STRENGTH OF ROUND COILS OF SMALL CROSS SECTION. H. B. Dwight and G. O. Peters, Massachusetts Institute of Technology

44-129. FUNDAMENTALS OF HEARING-AID DESIGN. W. D. Penn, Vacolite Company

9:30 a.m. Quality Control by Statistical Methods

CP.* DEVELOPMENTS IN THE CONTROL OF QUALITY BY STATISTICAL METHODS. R. E. Wareham, General Electric Company

CP.* EDUCATIONAL COURSES ON QUALITY CONTROL. Paul R. Rider, Washington University

CP.* APPLICATION OF STATISTICAL PRINCIPLES TO ACCEPTANCE INSPECTION OF ORDNANCE MATÉRIEL. Captain A. R. Burgess

44-113—ACO.† THE APPLICATION OF STATISTICS TO DIELECTRICS. C. M. Summers and K. E. Ross, General Electric Company

CP.* STATISTICAL METHODS FOR QUALITY CONTROL. Joseph Manuel, Westinghouse Electric and Manufacturing Company

12 m. Joint Luncheon With St. Louis Electrical Board of Trade

Address "Aviation and the Electrical Engineer," Lieutenant Colonel T. E. Holliday, United States Army Air Forces

2:00 p.m. Conference of Officers, Delegates, and Members

2:00 p.m. Power Transmission

44-114. THE MEASUREMENT OF LIGHTNING CURRENTS IN DIRECT STROKES. G. D. McCann, Westinghouse Electric and Manufacturing Company

44-115. TRANSMISSION-LINE ELECTRIC LOADINGS. S. B. Cray, General Electric Company

44-116. RING BUSES FOR GENERATING AND TRANSMISSION STATIONS. E. L. Michelson and J. P. Gallassini, Commonwealth Edison Company

44-117. CAPACITOR INSTALLATION AT NEWPORT NEWS V. R. Parrack, Virginia Public Service Company, and E. L. Harder, Westinghouse Electric and Manufacturing Company

44-118. CAPACITORS, CONDENSERS, AND SYSTEM STABILITY. J. W. Butler, T. W. Schroeder, and W. Ridgway, General Electric Company

44-119. A METHOD OF APPROACH TO THE CONSIDERATION OF POWER-DISTRIBUTION-SYSTEM COSTS. O. B. Falls, Jr., General Electric Company

2:00 p.m. Aircraft Ignition and Auxiliaries

44-112. AIRCRAFT STORAGE-BATTERY DESIGN. J. L. Rupp, National Battery Company

44-121. BATTERY BOOSTER COILS FOR AIRPLANE-ENGINE IGNITION SYSTEMS. A. V. Alvino, Bendix Aviation Corporation

44-123. DIMENSIONAL STUDY OF LIGHTWEIGHT MOTORS FOR AIRCRAFT. W. J. Morrill, Electric Motors and Specialties Company

44-124. AUXILIARY POWER-PLANT REQUIREMENTS. L. E. O'Neil, Andover Motors Corporation

2:00 p.m. Electric Welding

44-101. RATING OF ELECTRIC EQUIPMENT UNDER INTERMITTENT LOAD. Myron Zucker, Mackworth G. Rees, Inc.

44-125. AN IMPROVED ELECTRONIC CONTROL FOR CAPACITOR-DISCHARGE RESISTANCE WELDING. H. J. Michael and E. T. Hughes, Westinghouse Electric and Manufacturing Company

44-105. THE DESIGN OF LOW-VOLTAGE WELDING-POWER DISTRIBUTION. C. A. Adams, J. R. Fetcher, and A. C. Johnson, E. G. Budd Manufacturing Company

CP.* THE USE OF CONSTANT-CURRENT REGULATORS AND CAPACITORS TO PROVIDE SATISFACTORY DISTRIBUTION-SYSTEM DESIGN WHEN SERVING WELDING LOADS. E. R. Hendrickson and R. O. Askey, Public Service Company of Northern Illinois

Wednesday, June 28

10:00 a.m. General Session

2:00 p.m. Morse Telegraph Centennial

44-126. DEVELOPMENTS IN THE FIELD OF CABLE AND RADIOTELEGRAPH COMMUNICATIONS. Haraden Pratt, Mackay Radio and Telegraph Company, and J. K. Roosevelt, All America Cables and Radio, Inc.

44-127. AMERICAN TELEGRAPHY AFTER 100 YEARS. F. E. d'Humy and P. J. Howe, Western Union Telegraph Company

44-128. TELEGRAPHY IN THE BELL SYSTEM. R. D. Parker, Bell Telephone Laboratories, Inc., and J. A. Duncan and R. E. Pierce, American Telephone and Telegraph Company

2:00 p.m. Power Cables

44-130. IMPULSE STRENGTH OF INSULATED-POWER-CABLE CIRCUITS. Herman Halperin, Commonwealth Edison Company and G. B. Shanklin, General Electric Company

44-131. CYCLIC MOVEMENT OF CABLE—ITS CAUSES AND EFFECTS ON CABLE SHEATH LIFE. C. S. Schifreen, Philadelphia Electric Company

44-132. AN INVESTIGATION OF THE RELATIONSHIP BETWEEN TEMPERATURE AND MOVEMENT OF CABLES IN DUCTS. C. T. Nicholson and T. J. Brosnan, Buffalo Niagara Electric Corporation

44-133. GAS-FILLED CABLE RESEARCH AND EXPERIENCE. G. B. Shanklin, General Electric Company

44-134. OPERATION OF LOW-PRESSURE GAS-FILLED CABLE. C. T. Hatcher, Consolidated Edison Company of New York, Inc.

2:00 p.m. Aircraft Lighting and Instruments

44-136. GASEOUS-DISCHARGE LAMPS FOR AIRPLANE LIGHTING SERVICE. E. W. Beggs, Westinghouse Electric and Manufacturing Company

44-91. LIGHTING REQUIRED FOR COMMERCIAL AIRLINE AIRCRAFT. W. A. Petrash, American Airlines, Inc.

44-138. AIRCRAFT-ENGINE TORQUE METERS. F. W. Godsey, Jr. and B. F. Langer, Westinghouse Electric and Manufacturing Company

44-149. MAGNESYN REMOTE INDICATION. R. S. Childs, Bendix Aviation Corporation

2:00 p.m. Industrial Control

44-139. THE DEGREE OF SHORT-CIRCUIT PROTECTION AFFORDED SMALL LOW-VOLTAGE A-C AND D-C STARTERS BY MEANS OF FUSES AND CIRCUIT BREAKERS. B. W. Jones, General Electric Company

44-140. INSULATION TEMPERATURE STANDARDS FOR INDUSTRIAL-CONTROL COILS. B. W. Erikson, General Electric Company

44-141. INDUSTRIAL CONTROL: SHUNTED-ARMATURE CONNECTION FOR A D-C SHUNT MOTOR. G. F. Leland and L. T. Rader, General Electric Company

44-142. MODERN CARGO-WING CONTROL FOR USE ON VICTORY SHIPS. F. H. Holt, General Electric Company

CP.* GRID CONTROL FOR GASEOUS-DISCHARGE TUBES. P. T. Chin and E. E. Moyer, General Electric Company

2:00 p.m. Conference on Problems in Engineering Colleges and Their Effects in Industry

CP.* POSTWAR COURSES AND CURRICULA IN ELECTRICAL ENGINEERING. R. G. Kloeffer, Kansas State College

CP.* INTERPRETATION OF PRESENT HIATUS IN ELECTRICAL-ENGINEERING EDUCATION ON INDUSTRIAL POSTWAR DEMANDS FOR ENGINEERS. J. L. Hamilton, Century Electric Company

3:30 p.m. Clinic on College and High School Student Counseling

CP.* CO-OPERATION OF SECTIONS. G. W. Bowers, chairman, Sections committee

St. Louis, Mo., June 26-30, 1944

CP.* VALUES OF COUNSELING TO HIGH-SCHOOL STUDENTS. T. L. Jones, chairman, educational committee, St. Louis Section

CP.* HIGH-SCHOOL-STUDENT COUNSELING IN METROPOLITAN NEW YORK AREA. S. P. Shackleton, chairman, student guidance committee, New York Section

CP.* WAYS AND MEANS OF SECTIONS CO-OPERATING WITH COLLEGE AIEE BRANCHES. R. C. Gorham, University of Pittsburgh

Thursday, June 29

9:30 a.m. Symposium on Electronic Frequency Converters

44-143. HISTORY AND DEVELOPMENT OF THE ELECTRONIC POWER CONVERTERS. E. F. W. Alexanderson and E. L. Philippi, General Electric Company

44-144. THE ELECTRONIC CONVERTER FOR EXCHANGE OF POWER. F. W. Cramer, Carnegie-Illinois Steel Corporation, and L. W. Morton and A. G. Darling, General Electric Company

44-145. DESIGN OF AN ELECTRONIC FREQUENCY CHANGER. C. H. Willis, Princeton University, and R. W. Kuenning, E. F. Christensen, and B. D. Bedford, General Electric Company

44-146. SWITCHGEAR AND CONTROL FOR AN ELECTRONIC POWER CONVERTER. W. N. Gittings and A. W. Bateman, General Electric Company

44-147. PENTODE IGNITRONS FOR ELECTRONIC POWER CONVERTERS. H. C. Steiner, J. L. Zehner, and H. E. Zuvers, General Electric Company

9:30 a.m. Aircraft Instruments

44-152. A UNIQUE MOVING-MAGNET RATIO INSTRUMENT. F. R. Sias and D. B. Fisk, General Electric Company

44-153. RECENT ADVANCES IN AIRCRAFT-TACHOMETER DESIGN. R. G. Ballard and C. P. Hall, General Electric Company

44-150. DESIGN CONSIDERATIONS IN AIRCRAFT INSTRUMENTS TO MEET WAR SERVICE. C. F. Savage and J. M. Whittenton, General Electric Company

44-151. ELECTRICALLY OPERATED GYROSCOPIC INSTRUMENTS. H. Konet, Bendix Aviation Corporation

44-148. TOTALIZING CONTENTS OF AIRCRAFT FUEL TANKS. J. R. Macintyre, General Electric Company

9:30 a.m. Heating Houses Electrically

44-154. LOAD-CALCULATION PROCEDURE FOR ELECTRIC-PANEL SPACE HEATING. B. F. Raber and F. W. Hutchinson, University of California

44-155. ELECTROTHERMAL SPACE HEATING AND AIR CONDITIONING. G. H. Krueger, Bonneville Power Administration

44-156. POSSIBILITIES OF HEAT PUMPS FOR HEATING HOMES. R. U. Berry, General Electric Company

9:30 a.m. Conference on Temperature Standards

The purpose of the* conference sessions is to review temperature standards including hot-spot allowances for rotating machines in the fractional- and integral-horsepower sizes. These sessions represent a continuation of the activity started at the winter technical meeting in New York, N. Y., January 24-28, 1944. There will be a series of conference papers presented giving actual test results of temperature tests on various types and sizes of motors.

Those expected to present conference papers are as follows:

L. E. Hildebrand, General Electric Company

L. H. Hirsch, Century Electric Company

W. R. Hough, Reliance Electric and Engineering Company

H. M. Joy, Master Electric Company

T. C. Lloyd, Robbins and Meyers, Inc.

R. F. Munier, Emerson Electric Manufacturing Company

F. D. Phillips, General Electric Company

M. L. Schmidt, General Electric Company

P. H. Trickey, Diehl Manufacturing Company

C. P. Potter, Wagner Electric Corporation

2:00 p.m. Conference on Temperature Standards (continued)

2:00 p.m. Switchgear

44-157. PROTECTION OF LARGE D-C MACHINES BY MEANS OF HIGH-SPEED CIRCUIT BREAKERS. J. Elmer Housley, Aluminum Company of America and Otto Jensen, I-T-E Circuit Breaker Company

44-102. A PNEUMATIC MECHANISM FOR OUTDOOR OIL CIRCUIT BREAKERS. L. J. Linde and E. B. Rietz, General Electric Company

44-158. IMPROVED SELECTIVE TRIPPING OF LOW-VOLTAGE AIR CIRCUIT BREAKERS. C. P. West, Westinghouse Electric and Manufacturing Company

44-97. FUSING PRACTICES ON DISTRIBUTION SYSTEMS—II. J. S. Parsons and J. M. Wallace, Westinghouse Electric and Manufacturing Company

44-159. FAULT PROTECTION ON SHIPBOARD A-C POWER-DISTRIBUTION SYSTEMS. Captain H. G. Rickover and P. N. Ross, Bureau of Ships, Navy Department

2:00 p.m. Electronics and Measurements

44-78. DEVELOPMENT OF EXCITRON-TYPE RECTIFIER. H. Winograd, Allis-Chalmers Manufacturing Company

44-11. ANALYSIS OF RECTIFIER CIRCUITS. E. F. Christensen and C. C. Herskind, General Electric Company, and C. H. Willis, Princeton University

44-160. OPERATION OF RECTIFIERS UNDER UNBALANCED CONDITIONS. E. F. Christensen and M. M. Morack, General Electric Company

44-161. A RESONANT-CAVITY METHOD FOR MEASURING DIELECTRIC PROPERTIES AT ULTRAHIGH FREQUENCIES. C. N. Works, T. W. Dakin, and F. C. Boggs, Westinghouse Electric and Manufacturing Company

C.P.* HIGH-FREQUENCY CABLE DESIGN AND TESTING. N. D. Kennedy, P. W. Ware, Simplex Wire and Cable Company

2:00 p.m. Conference on Experiences With Electric House Heating

CP.* ELECTRIC HEATING OF SMALL HOMES IN THE TENNESSEE VALLEY. B. H. Martin, Tennessee Valley Authority

CP.* REVERSE REFRIGERATION APPLIED TO A NEW HAVEN OFFICE BUILDING. E. H. Walton and C. A. Williams, United Illuminating Company

4:00 p.m. Open Meeting of Committee on Domestic and Commercial Applications

CP.* REPORT OF SUBCOMMITTEE ON FARM APPLICATION. C. H. Leatham, Monongahela West Penn Public Service Company

CP.* REPORT OF SUBCOMMITTEE ON HAZARDS TO FARM ANIMALS. W. B. Buchanan, Hydro-Electric Power Commission of Ontario

CP.* REPORT OF SUBCOMMITTEE ON WIRING MATTERS. Wesley Weinert, Philadelphia Electric Company

Friday, June 30

9:30 a.m. Electrochemistry and Electrometallurgy

44-163. THE COPPER-OXIDE RECTIFIER IN ELECTRO-CHEMICAL WORK. I. R. Smith, Westinghouse Electric and Manufacturing Company

44-164. ELECTRONIC REGULATOR FOR ARC FURNACES. J. E. Reilly and C. E. Valentine, Westinghouse Electric and Manufacturing Company

44-165. CHARACTERISTICS OF CHLORINATED IMPREGNANTS IN D-C PAPER CAPACITORS. L. J. Berberich, C. V. Fields, and R. E. Marbury, Westinghouse Electric and Manufacturing Company

44-100. TREATMENT AND CASTING OF METALS BY ELECTROMAGNETIC FORCES. W. W. Hoke, Garden City, N. Y.

44-166. INDUCTION HEATING—SELECTION OF FREQUENCY. N. R. Stansel, General Electric Company

44-167-ACO.† APPLICATION OF INDUSTRIAL GENERATORS TO INDUCTION HEATING. E. H. Browning, Westinghouse Electric and Manufacturing Company

44-168. SURFACE HEATING BY INDUCTION. H. F. Storm, Allis-Chalmers Manufacturing Company

44-99. VOLTAGE TRANSIENTS IN ARC-FURNACE CIRCUITS. Subcommittee on transient voltages in arc-furnace circuits

9:30 a.m. Transformers

44-169. PROGRESS IN IMPULSE TESTING OF TRANSFORMERS. J. H. Hagenguth, General Electric Company

44-170. HIGH-VOLTAGE COMPRESSED-GAS POWER TRANSFORMERS. H. M. Hobart, consulting engineer

44-171. THE DESIGN AND OPERATING CHARACTERISTICS OF MODERN DRY-TYPE AIR-COOLED TRANSFORMERS. W. W. Satterlee, Westinghouse Electric and Manufacturing Company

44-103. HOT-SPOT TEMPERATURES IN DRY-TYPE TRANSFORMER WINDINGS. H. C. Stewart and L. C. Whitman, General Electric Company

CP.* STANDARD CURRENT TRANSFORMERS WITH ONE-AMPERE SECONDARY WINDING. L. F. Hunt and J. H. Vivian, Southern California Edison Company, Ltd.

9:30 a.m. Industrial Power Applications

44-178. EXTENDING THE USE OF SHUNT CAPACITORS BY MEANS OF AUTOMATIC SWITCHING. W. H. Cuttino, Westinghouse Electric and Manufacturing Company

44-173. AUTOMATIC CONTROL AND SWITCHING EQUIPMENT FOR CAPACITOR BANKS AND ITS APPLICATION. T. W. Schroeder and W. C. Bloomquist, General Electric Company

CP.* ELECTRIC-POWER DISTRIBUTION FOR INDUSTRIAL PLANTS. Report of AIEE committee on industrial power applications

CP.* DODGE CHICAGO PLANT'S ELECTRIC-POWER-DISTRIBUTION SCHEME WITH AIRPLANE-ENGINE TESTING POWER-RECOVERY CIRCUITS. E. L. Bailey, Chrysler Corporation

2:00 p.m. Relays

44-104. BIBLIOGRAPHY OF RELAY LITERATURE 1940-43. Working group on relay bibliography, AIEE relay subcommittee

44-172. A NEW FREQUENCY RELAY FOR POWER-SYSTEM APPLICATIONS. H. J. Carlin and J. L. Blackburn, Westinghouse Electric and Manufacturing Company

44-94. THE EVOLUTION OF STANDARD LINES OF CURRENT TRANSFORMERS FOR HIGH OVERCURRENT CAPACITY. E. C. Wentz, Westinghouse Electric and Manufacturing Company

44-93. CURRENT-TRANSFORMER OUTPUT AND APPLICATION CHARTS. R. Koller, Pacific Electric Manufacturing Corporation

44-135. A NEW CARRIER RELAYING SYSTEM. T. R. Halman and A. F. Drompp, Detroit Edison Company and S. L. Goldsborough and H. W. Lensner, Westinghouse Electric and Manufacturing Company

2:00 p.m. Land Transportation

44-92. MODERN MOTIVE POWER FOR THE SOROCABANA RAILWAY. R. L. Chapman and O. K. Kjelseth, General Electric Company

44-96. ECONOMICS OF TROLLEY-COACH OPERATION. G. M. Woods, Westinghouse Electric and Manufacturing Company

2:00 p.m. Motors and Related Subjects

44-174. INTERLAMINATION RESISTANCE. J. P. Barton, Carnegie-Illinois Steel Corporation

44-175. TRANSIENT PERFORMANCE OF INDUCTION MOTORS. F. J. Maginniss and N. R. Schultz, General Electric Company

44-176. DIFFERENTIAL LEAKAGE WITH RESPECT TO THE FUNDAMENTAL WAVE AND TO THE HARMONICS. M. M. Liwchitz, Westinghouse Electric and Manufacturing Company

44-177. THE NATURE OF VIBRATION IN ELECTRIC MACHINERY. T. D. Graybeal, University of California

*CP: Conference presentation; no advance copies of papers available; not intended for publication in Transactions.

†ACO: Advance copies only available; not intended for publication in Transactions.

Section and Branch Activities—Annual Report for 1943-44

The following constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1944. Similar information for three preceding fiscal years appeared in *Electrical Engineering* in June 1943, pages 264-5; June 1942, pages 322-3; June 1941, pages 285-7.

Present members of the Sections committee

and the committee on Student Branches, which supervise the divisions of Institute activities covered by this report, are:

Sections—G. W. Bower, chairman; R. M. Pfalzgraff, vice-chairman; A. C. Muir, secretary; O. C. Brill, M. S. Coover, C. A. Faust, Frederick Krug, S. J. Lisberger, E. T. Mahood, W. B. Morton, C. S. Purnell, E. W. Schilling, J. M. Thomson, and, ex officio, the chairmen of all Sections of the Institute.

Branches—R. G. Warner, chairman; E. W. O'Brien, vice-chairman; H. H. Henline, secretary; L. A. Bingham; H. L. Davis, Jr.; A. G. Ennis; Everett S. Lee; H. C. Madsen; E. M. Strong; and, ex officio, all Student Branch counselors.

Table II. Branch Meetings Held During Year Ending April 30, 1944

Branch	Number	Average Attendance
Akron, University of.....	14	
Alabama Polytechnic Institute.....	14	
Alabama, University of.....	9	11
Alberta, University of.....	9	32
Arizona, University of.....	4	10
Arkansas, University of.....	2	12
British Columbia, University of.....	13	27
Brooklyn, Polytechnic Institute of		
Day division.....	12	28
Evening division.....		
Brown University.....	11	12
Bucknell University.....	5	33
California Institute of Technology.....	1	14
California, University of.....	9	31
Carnegie Institute of Technology.....	27	34
Case School of Applied Science.....	5	24
Catholic University of America.....	4	6
Cincinnati, University of.....	3	21
Clarkson College of Technology.....	7	22
Clemson Agricultural College.....	3	13
Colorado State College.....	7	12
Colorado, University of.....	11	42
Columbia University.....	1	27
Connecticut, University of.....	5	55
Cooper Union		
Day division.....	7	24
Evening division.....	1	12
Cornell University.....	11	76
Delaware, University of.....		
Denver, University of.....	3	14
Detroit, University of.....		
Drexel Institute of Technology.....	7	11
Duke University.....	8	28
Florida, University of.....		
George Washington University.....	7	27
Georgia School of Technology.....	1	10
Harvard University.....		
Idaho, University of.....	12	14
Illinois Institute of Technology.....		
Illinois, University of.....	10	27
Iowa State College.....	9	65
Iowa, University of.....	19	18
Johns Hopkins University.....	2	30
Kansas State College.....	13	42
Kansas, University of.....	4	16
Kentucky, University of.....	4	18
Lafayette College.....	3	33
Lehigh University.....	9	47
Louisiana State University.....	12	15
Louisville, University of.....	4	26
Maine, University of.....		
Manhattan College.....	1	17
Marquette University.....	9	21
Maryland, University of.....	9	14
Massachusetts Institute of Tech-		
nology.....	4	75
Michigan College of Mining and		
Technology.....	6	24
Michigan State College.....	4	18
Michigan, University of.....	10	41
Milwaukee School of Engineering.....	3	15
Minnesota, University of.....	1	125
Mississippi State College.....	3	14
Missouri School of Mines and		
Metallurgy.....	6	39
Missouri, University of.....	4	51
Montana State College.....	20	11
Nebraska, University of.....	17	32
Nevada, University of.....	6	7
Newark College of Engineering.....	6	20
New Hampshire, University of.....	7	24
New Mexico State College.....		
New Mexico, University of.....	11	30

Table I. Section Membership and Meetings During Year Ending April 30, 1944

Section	AIEE Members August 1942	AIEE Members August 1943	Number of Meetings	Average Attendance
Akron.....	94	87	8	67
Alabama.....	44	42	3	
Arizona.....	37	37	9	43
Boston.....	516	575	8	227
Special technical meet-				
ing.....			1	32
Central Indiana.....	133	132	10	202
Chicago.....	836	849	7	150
Power group.....			4	77
Industrial group.....			3	73
Communication group.....			2	92
Cincinnati.....	214	151	9	90
Cleveland.....	376	368	9	112
Special technical meet-				
ings.....			3	55
Columbus.....	95	82	5	78
Zanesville Subsection.....			12	21
Connecticut.....	333	361	8	118
Dayton.....		122	7	93
Aircraft electrical				
group.....			3	101
Denver.....	180	186	9	88
East Tennessee.....	145	134	10	49
Erie.....	65	71	7	27
Florida.....	111	136	4	24
Fort Wayne.....	93	100	8	53
Georgia.....	119	101	10	80
Houston.....	133	153	8	80
Beaumont Subsection.....			4	80
Iowa.....	84	80	12	39
Ithaca.....	53	60	8	97
Kansas City.....	140	143	10	88
Lehigh Valley.....	188	189	8	69
Los Angeles.....	540	548	10	183
Aircraft division.....			6	180
Electronics division.....			6	262
Louisville.....	73	75	11	30
Lynn.....	186	202	7	174
Popular lectures.....			4	1,350
Madison.....	73	75	5	9
Rock River Valley				
Subsection.....			5	80
Mansfield.....	71	68	7	63
Maryland.....	322	349	8	172
Memphis.....	56	57	10	35
Mexico.....	53	57	11	105
Michigan.....	418	398	6	315
Round-table meetings.....			5	69
Industrial power com-				
mittee.....			2	135
Milwaukee.....	313	338	8	189
Power applications				
and control.....			4	33
Electronics.....			5	64
Electrical machinery.....			4	25
Minnesota.....	98	118	12	44
Power group meeting.....			1	45
Montana.....	45	40	9	97
Montreal.....		148	12	91
Ottawa Subsection.....			2	40
Muscle Shoals.....	33	23	4	
Nebraska.....	59	50	5	36
New Mexico—West Texas.....	43	48	8	18
New Orleans.....	133	141	9	57
New York.....	3,447	3,586	4	210
Communication group.....			4	233
Power and industrial				
group.....			5	384
Transportation group.....			3	391
Basic science group.....			4	208
Illumination group.....			4	201
Niagara Frontier.....	198	186	9	84
Niagara Falls Sub-				
section.....			4	55
North Carolina.....	107	99	2	77
North Texas.....	170	164	7	58
Oklahoma City.....	104	90	8	75
Philadelphia.....	809	863	8	107
Aircraft electrical en-				
gineering discussion				
group.....			3	24
Instruments and meas-				
urements group.....			3	83
Communication dis-				
cussion group.....			4	150
Industrial-practice dis-				
cussion group.....			3	32
Power discussion				
group.....			2	49
Foremen's discussion				
group.....			6	17
Pittsburgh.....	662	657	9	154
Pittsfield.....	194	195	7	103
Popular lectures.....			6	1,175
Portland.....	196	177	10	77
Transmission and dis-				
tribution committee.....			2	66
Communication com-				
mittee.....			2	36
Providence.....	100	93	8	85
Rochester.....	112	121	9	116
Luncheon meetings.....			4	43
St. Louis.....	360	295	10	106
San Diego.....	54	56	8	62
San Francisco.....	549	601	17	109
Schenectady.....	559	630	9	159
Seattle.....	230	249	10	146
Sharon.....	153	162	9	74
South Bend.....	58	48	10	54
South Carolina.....	53	55	2	60
South Texas.....	53	50	8	30
Spokane.....	82	85	7	42
Springfield.....	52	51	6	85
Syracuse.....	119	129	5	84
Toledo.....	89	88	8	138
Toronto.....	396	379	11	200
Hamilton Subsection.....			7	
Tulsa.....	87	79	9	47
Urbana.....	78	77	4	33
Illinois Valley Sub-				
section.....			10	58
Utah.....	64	85	7	52
Vancouver.....	95	98	11	78
Virginia.....	150	147	3	110
Washington.....	600	675	8	220
West Virginia.....	39	38	6	65
Wichita.....	57	62	11	48
Worcester.....	63	57	7	80
Totals.....	16,844	17,321	738	
Total Sections 73	Total attendance, 83,120			

Table II. (Continued)		
Branch	Number	Average Attendance
New York, College of the City of		
Day division.....	12.....	78
Evening division.....		
New York University		
Day division.....	1.....	20
Evening division.....	5.....	14
North Carolina State College.....	7.....	16
North Dakota Agricultural College.....	2.....	5
North Dakota, University of.....		
Northeastern University.....	6.....	45
Northwestern University.....	2.....	30
Norwich University.....		
Notre Dame, University of.....	6.....	19
Ohio Northern University.....	11.....	18
Ohio State University.....	5.....	26
Ohio University.....		
Oklahoma Agricultural and Mechanical College.....		
Oklahoma, University of.....	6.....	20
Oregon State College.....	6.....	64
Pennsylvania State College.....	4.....	32
Pennsylvania, University of.....	1.....	23
Pittsburgh, University of.....	46.....	83
Puerto Rico, University of.....		
Pratt Institute.....	8.....	45
Princeton University.....	1.....	20
Purdue University.....	8.....	164
Rensselaer Polytechnic Institute.....	3.....	41
Rhode Island State College.....		
Rice Institute.....	5.....	26
Rose Polytechnic Institute.....	8.....	16
Rutgers University.....	4.....	17
Santa Clara, University of.....	8.....	10
South Carolina, University of.....	9.....	22
South Dakota State College.....	1.....	7
South Dakota State School of Mines.....	3.....	21
Southern California, University of.....	11.....	20
Southern Methodist University.....	3.....	28
Stanford University.....	4.....	41
Stevens Institute of Technology.....		
Swarthmore College.....	3.....	17
Syracuse University.....	1.....	16
Tennessee University of.....	19.....	25
Texas Agricultural and Mechanical College.....		
Texas Technological College.....	3.....	29
Texas, University of.....	2.....	20
Tufts College.....	3.....	72
Tulane University.....	8.....	19
Union College.....	10.....	35
Utah, University of.....	4.....	30
Vanderbilt University.....		
Vermont, University of.....		
Villanova College.....	7.....	33
Virginia Military Institute.....		
Virginia Polytechnic Institute.....	16.....	27
Virginia, University of.....		
Washington, State College of.....	4.....	29
Washington, University of.....	3.....	53
Washington University.....	9.....	18
West Virginia University.....	19.....	14
Wisconsin, University of.....	9.....	33
Worcester Polytechnic Institute.....		
Wyoming, University of.....	1.....	9
Yale University.....	3.....	143
Total—125 Branches		

Table III. Section Meetings Held During Last Three Fiscal Years			
	Fiscal Year Ending April 30		
	1942	1943	1944
Number of Sections.....	72 ..	73 ..	73
Number of meetings held.....	647 ..	598 ..	738
Average number of meetings.....	9.0 ..	8.2 ..	10.1
Total attendance.....	78,254 ..	66,111 ..	83,120
Average attendance per meeting.....	121 ..	112 ..	112.6

Table IV. Branch Meetings Held During Last Three Fiscal Years			
	For Year Ending April 30		
	1942	1943	1944
Number of Branches.....	124 ..	125 ..	125
Number of meetings held.....	946 ..	942 ..	755
Average number of meetings.....	7.6 ..	7.5 ..	6.0
Total attendance.....	37,785 ..	38,227 ..	24,768
Average attendance per meeting.....	39.9 ..	40.6 ..	32.8

Table VI. Section or Joint Section and Branch Meetings With Active Student Participation				
Sections	Branches	Date	Student Talks	Attendance
Urbana.....	University of Illinois.....	5/28/43.....	2.....	13
North Carolina.....	North Carolina State College.....	11/8/43.....	1.....	81
Akron.....	University of Akron.....	1/11/44.....	4.....	49
North Texas.....	Southern Methodist University.....	1/24/44.....	3.....	52
New Orleans.....	Tulane University.....	2/9/44.....	1.....	54
Vancouver.....	University of British Columbia.....	3/6/44.....	4.....	71
Chicago.....	{ Illinois Institute of Technology Northwestern Technological Institute }	4/11/44.....	4.....	28
Lehigh Valley.....	{ Bucknell University Lehigh University }	4/14/44.....	1.....	163
Iowa.....	University of Iowa.....	4/21/44.....	5.....	
Totals—9 Sections, 11 Branches, 9 meetings.....				511

Subsection Formed in Ottawa

The newest addition to the Institute's lengthening list of Subsections was formed in Ottawa, Ont., February 9, 1944, within the territory of the Montreal Section.

The 11 members and 21 nonmembers present elected the following officers:

Chairman, B. G. Ballard (A '33) associate research engineer, National Research Council.

Vice-chairman, W. G. C. Gliddon (A '28) chief engineer, Gatineau Power Company.

Secretary, J. H. Simpson (A '39) junior research engineer, National Research Council.

Discussion of the relationship of the AIEE with the Engineering Institute of Canada defined the former as filling the technical needs of electrical engineers and left such general questions as the professional status of the engineer within the province of the Engineering Institute of Canada.

At an executive meeting of the Subsection held February 16, the following committee was appointed to draft the necessary bylaws: W. G. C. Gliddon; E. G. Cullwick (M '33) lieutenant commander in the Royal Canadian Naval Volunteer Reserve; and D. S. Smith (A '33) junior research engineer, National Research Council.

1944 Lamme Medal Nominations Due December 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the AIEE Lamme Medal, to be awarded early in 1945, may be submitted by any member in accordance with section 1 of article VI of the bylaws of the Lamme Medal committee, as follows:

The committee shall cause to be published in one or more issues of *Electrical Engineering*, or of its successors,

Table V. Conferences on Student Activities		
District	Location	Date
5.....	Chicago, Ill.....	6/19/43
8 and 9 and University of British Columbia	{ Salt Lake City, Utah (Pacific Coast technical meeting).....	9/3/43
4.....	Roanoke, Va. (Southern District technical meeting).....	11/17/43
2.....	Pittsburgh, Pa.....	1/11/44
1.....	Boston, Mass. (North Eastern District technical meeting)....	4/19/44

each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by December 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least three engineers of standing, who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified in the foregoing quotation.

ABSTRACTS . . .

TECHNICAL PAPERS previewed in this section will be presented at the AIEE summer technical meeting, St. Louis, Mo., June 26-30, 1944, and are expected to be ready for distribution in advance pamphlet form within the current month. Copies may be obtained by mail from the AIEE order department, 33 West 39th Street, New York 18, N. Y., at prices indicated with the abstract; or at five cents less per copy if purchased at AIEE headquarters or at the meeting registration desk.

Mail orders will be filled
AS PAMPHLETS BECOME AVAILABLE

Air Transportation

44-89—The Differential Generator-Control Relay for D-C Aircraft Electric Systems; F. E. Crever (A '27). 20 cents. The characteristics of both the definite pick-up type of generator control relay and the new differential type are analyzed and compared

from the standpoint of chatter. Also, it is explained how equalizing coils on the regulators of the generators enable positive action in coming on a live bus with differential-type relays. The results of flight tests on a four-engined airplane are shown by oscillograms recorded in flight which substantiate the contention that the differential type is superior. An analysis of a system of *N* generators in parallel is made for the purpose of determining the percentage load necessary to cause any relay to close on its generator. It is shown that for a given differential setting and equalizer strength this is a fixed percentage load of the connected generators regardless of the number of generators on or off the bus.

44-88—A-C Contactors for Aircraft; *F. J. Russell (M '37), A. P. Charbonneau (Application pending).* 15 cents. Use of a-c power systems on aircraft presents the problem of providing suitable switching apparatus. Contactors with the desired characteristics and of suitable size and weight have not been available. An analysis is made of contactor ratings and performance characteristics to fill the needs of proposed aircraft. Many of the problems encountered in designing contactors to meet these requirements are discussed. Contactors with continuous current ratings from 5 to 100 amperes and a circuit breaker, rated at 120 amperes with a short circuit capacity of 4,000 amperes for use on 208-volt three-phase 400-cycle systems, are illustrated and described.

44-90—Aircraft Fuses Must Protect; *J. C. Lebens, Jr. (A '41),* 15 cents. The evolution of the electrical system in aircraft has paralleled the development of the plane itself. Today, when the very heart of the airplane is its electrical system, faulty operation of protective devices cannot be countenanced. Complete protection can be obtained only by a device having the same time-current characteristic as that of the equipment it is protecting. This paper covers the fundamentals involved in the protection problem and describes a method whereby it can be solved by adapting a device, already proved in power applications, to meet the requirements imposed by aircraft.

44-108—An Aircraft Differential-Voltage Cutout; *O. C. Walley (A '44).* 15 cents. Experience obtained with present multiengine aircraft electric systems indicates a need for preventing interchange of current between generators when the system is operating at light loads. Such current interchange causes reverse-current cutouts of conventional design to connect and disconnect their respective generators to the system so rapidly that the action is called "chatter." Conventional cutouts connect the generator to the system when the generator voltage is above a preset value. The differential-voltage reverse-current cutout connects the generator to the system when the generator voltage is a preset value above the system voltage. A description is given on the design, operation, and advantages of a differential-voltage reverse-current cutout which prevents interchange of current between the generators.

44-91—Lighting Required for Commercial Airline Aircraft; *W. A. Petrask (A '36).*

15 cents. A review of the lighting requirements of commercial-airline aircraft discloses the need for additional development of aircraft-lighting equipment. All phases of the aircraft-lighting problem are discussed and the applicable Civil Aeronautics Authority regulations presented. Actual airline operating experience forms the basis for the stated requirements. The subject logically is divided into two general classifications, namely, internal and external lighting. Under the heading of external lighting are the position lights, landing lights, wing-ice lights, and wheel lights. Among the internal lights discussed are the cabin, compartment, and cockpit lights. The relative advantages and disadvantages of the various types of instrument-panel lighting are given, and the importance of suitable cockpit lighting is stressed. The greatest postwar improvement is expected to be the application of fluorescent lighting to the aircraft cabin.

44-124—Auxiliary-Power-Plant Requirements; *L. E. O'Neil.* 15 cents. Designers of electrical equipment for aircraft are confronted with many limitations. Some of these limitations may be nullified by the use of auxiliary power plants. To cover various phases of application a series of engine generators would be necessary. A large number of their design features should be adapted to each type of airplane in order to save weight and obtain best performance. This necessitates close co-operation between designers of the component parts of the airplane.

44-136—Gaseous-Discharge Lamps for Airplane-Lighting Service; *E. W. Beggs.* 15 cents. Fluorescent lamps function well on 400-cycle alternating current which is widely used in airplanes. The efficiency is increased about 20 per cent and, of course, flicker is practically eliminated. Tests showed slightly less drop in lumen output with low-temperature ambient air when operated on 400-cycle instead of on 60-cycle current. Dependable low-temperature starting also is readily obtainable at the higher frequency by means of a small condenser in series with the starting switch of a thermal starter. The 400-cycle operation results in low lamp volts and high amperes for normal lamp wattage. The low lamp voltage provides steady operation but the high-ampere value tends to overload the electrodes somewhat so that to achieve long life the lamps should be run somewhat below normal wattage. The starting voltage of neon-glow lamps on 400-cycle systems is appreciably higher than on 60 cycles. These lamps are practically unaffected by low ambient temperatures on either frequency.

44-148—Totalizing Contents of Aircraft Fuel Tanks; *J. R. Macintyre (A '41).* 15 cents. In an airplane using more than one instrument to indicate the fuel quantity in its tanks, the pilot must add the readings of all instruments to learn his total fuel supply. A single-dial totalized indication of the fuel supply is desirable, because it saves the all-important factor of time, in addition to eliminating the possibility of arithmetical error. The problem of totalizing two or more liquid levels in aircraft fuel tanks falls into two broad classifications. The first of

these involves the addition of levels in a single tank where the sequence of use is definitely established. The second covers the totalization of several liquid levels in different tanks, where the sequence of use may vary widely with conditions. This paper describes methods for accomplishing both types of totalizing by means of a remote indicating equipment consisting of transmitter units installed in the fuel tanks and connected electrically to a moving-magnet ratio-type instrument.

44-138—Aircraft-Engine Torque Meters; *F. W. Godsey, Jr. (M '36), V. F. Langer.* 15 cents. Flight operations experience has shown that significant improvements in fuel economy may be obtained through the use of aircraft-engine torquemeters as regular flight instruments. This paper describes the better-known types of torquemeters and introduces a new type that recently has come through its development stage.

44-150—Design Considerations in Aircraft Instruments to Meet War Service; *C. F. Savage (M '43), J. M. Whittenton (A '37).* 25 cents. New conditions imposed by the rapid advancement in aviation have challenged industry to develop instruments capable of meeting rigid war requirements. This paper describes generally and specifically how the design features of aircraft instruments have been influenced by wide ranges of operating temperatures, extreme conditions of shock and vibration, extension of altitude ranges, world-wide climatic conditions, adoption of new power supplies for aircraft, standardization of mechanical features necessary because of large-scale use, and the requirements of servicing. The design features discussed are generally applicable to all aircraft instruments.

44-152—A Unique Moving-Magnet Ratio Instrument; *F. R. Sias, D. B. Fisk.* 15 cents. A unique type of moving-magnet d-c ratio instrument is described in this paper. Its performance characteristics compare favorably with those of moving-coil instruments and, in addition, it has the characteristics of simplicity, ruggedness, and compactness. The instrument is readily adaptable to the measurement of temperature by means of bridge circuits utilizing resistance bulb detectors. In this type of circuit the instrument is compensated well for voltage and ambient temperature variations. Inferred uses include the measurement of ohms, current ratios, voltage ratios, telemetering, and voltage-weighted current indications. The structure includes a diametrically magnetized moving element, a dual-purpose damping structure and coil form, two mutually perpendicular sets of coils, and an enclosing magnetic return path and shield. The direction of the vector, resultant of the fluxes caused by currents in the two sets of coils, determines the position of the moving element.

44-153—Recent Advances in Aircraft-Tachometer Design; *R. G. Ballard (A '42), C. P. Hall.* 15 cents. This paper discusses the requirements of the magnetic-drag-type tachometer system in wartime production, involving increased operating temperature range, durability in service, and a new degree

of instrument compactness. During the past three years the existing designs have been revised and new designs developed to meet these requirements; the outstanding features and operating characteristics of the new designs are outlined in this article. The design factors involved in both the generators and indicators are broken down to give a detailed report of operating torques and voltages, high- and low-temperature influences on ball bearing life, development of new magnetic materials, and action of luminescent-coated pointers with temperature changes. The paper points out the special applications for tachometer equipment and the probable future trends.

44-112—Aircraft-Storage-Battery Design; J. L. Rupp. 15 cents. The paper points out wherein the aircraft-battery requirements differ from battery requirements encountered heretofore. Then step-by-step each of the important parts that complete the unit are described and information is given about what has been done in design to cause each part to provide a performance to meet aircraft usage. Attention is called to certain departures that have been made from what may be considered sound practice and reasons for the departures are given. Suggestions for correcting these departures are made and experimental work that is being carried on for further improvement is mentioned. In summarizing the data and experience accumulated a suggested design is offered which should overcome the present deficiencies and meet present requirements.

44-121—Battery Booster Coils for Airplane-Engine Ignition Systems; A. V. Aloino. 15 cents. Starting of airplane engines always has provided a problem from the ignition engineer's point of view and many innovations have been introduced in an attempt to provide ideal ignition without increasing the weight of the system. A source of external high-voltage current is provided for starting purposes when it becomes impossible to rotate the engine crankshaft fast enough to produce "coming-in speed" of the magneto. This source may be in the form of a booster magneto, high-voltage booster coil, or low-voltage starting vibrator. The high-voltage booster coil of the vibratory type has superseded the motor or manually operated magneto. It is a device for obtaining a high intermittent voltage from a source of steady low voltage by electromagnetic induction. The low-voltage starting-vibrator method consists of a separate induction coil connected to the magneto primary utilizing it as a transformer and supplying it with alternating impulses of about 150 volts.

44-149—Magnesyn Remote Indication; R. S. Childs. 15 cents. Electrical remote-indication systems fulfill an important function on modern aircraft. This paper describes in detail the Magnesyn system of remote indication and includes a brief review of other methods. Magnesyns are a-c-operated devices utilizing permanent magnet rotors at both transmitter and receiver. They have been used widely in remote-indicating compasses but are adaptable to many other problems. The development of the system, theory of operation, performance

features, and some applications of the system are discussed.

44-151—Electrically Operated Gyroscopic Instruments; H. Konet. 15 cents. Because of the increased use of electricity on aircraft, electrically operated gyroscopic instruments have been used for more applications. This paper described several types of gyro motors and their applications. It also cites the advantages of the electrical gyro over the air-driven gyro.

Basic Sciences

44-95—Formulas for the Four-Terminal-Network Parameters of Uniform-Ladder Networks; W. R. LePage (M'44). 15 cents. Uniform-ladder networks usually are treated in terms of their propagation function and characteristic impedances. However, when dealing with only the terminal quantities one is interested in the so-called *A-B-C* parameters, or the driving point and transfer impedances or admittances. These are related to the propagation function by hyperbolic functions; but they are actually rational functions of p ($p = d/dt$) or frequency. These rational functions are simplest for the *A-B-C* parameters and the driving point and transfer parameters are related to them by simple forms. Therefore, the treatment is in terms of the former. It is shown that the *A-B-C* parameters are all polynomials in the variable $Z_T T_T$, where these are the total series impedance and shunt admittance of the network, respectively. Explicit formulas are developed for the coefficients of these polynomials for mid-series or mid-shunt termination and the relations between the degrees of the polynomials and the number of network sections easily is established from these formulas.

44-109—Formulas for Calculating Short-Circuit Forces Between Channels Located Back to Back; T. J. Higgins (A'40). 15 cents. Formulas are derived for calculating the short-circuit mutual electromagnetic forces exerted between the two conductors of a single-phase bus comprised of channels located back to back. It is assumed that the conductors are nonmagnetic, are of such length that end effects are negligible, and carry currents distributed uniformly over the cross sections and that these cross sections are so thin they may be considered to be comprised of line segments. Once the desired formulas are obtained—through differentiation of the known formula for the inductance of the bus—their use is illustrated by calculation of a typical problem.

44-110—The Computation of Magnetic-Field Strength of Round Coils of Small Cross Section; H. B. Dwight (F'26), G. O. Peters. 15 cents. Formulas for the magnetic-field strength near a single round turn of fine wire were published by Andrew Gray and Alexander Russell and have been found very useful with coils the dimensions of whose cross sections are small compared with their radii. In this paper, correction formulas are given to improve the precision of that calculation by bringing in the effect of the section dimensions of length and thickness. The

correction terms are comparatively simple. They apply where the distance from the center of the round coil to the point where the field strength is to be computed is distinctly larger than the coil radius or else distinctly smaller. For the latter case, a second set of correction terms is given. A numerical example is given and the time saved by using the correction formulas in a favorable case, instead of other calculations which give equal precision, is shown.

Communications

44-126—Developments in the Field of Cable and Radiotelegraph Communications; Haraden Pratt (F'37), J. K. Roosevelt (M'30). 15 cents. This paper reviews the growth, from time of organization to the present, of each of the four telegraph communication companies constituting the system of the International Telephone and Telegraph Corporation which provide services between the United States and foreign countries. These are the All America Cables and Radio, Inc., the Commercial Cable Company, the Commercial Pacific Cable Company, and the Mackay Radio and Telegraph Company. Important elements in the technical developments applicable to the operation of both submarine-cable systems and radiotelegraph systems also are reviewed, showing how the methods and instrumentalities of today grew by process of evolution out of the elementary ways of the early days.

44-127—American Telegraphy After 100 Years; F. E. d'Humy (F'30), P. J. Howe (A'09). 30 cents. The telegraph, which is the oldest electrical industry, celebrated its centennial May 24 of this year. Technically, its operations have changed greatly during recent years, but the only data which have been published regarding such changes pertain to specific applications or developments. The present paper is intended to present an over-all picture of American telegraphy, as it is conducted today by the one company which is engaged solely in the telegraph business. The paper describes the nature of telegraph service, discusses the traffic problems associated with the business, and describes the facilities which are employed and the functions which they perform. Although the paper is long by reason of the multiplicity of telegraph services and types of apparatus, only brief references are made to features of plant or equipment which have become stabilized through the years and well understood by the industry. Similarly, no attempt is made to discuss details of technical design or operation, nor the various historical steps by which the telegraph reached its present status. In brief, the paper presents merely a general view of the industry, and a bibliography of its literature, from which anyone who seeks more details, can be guided in his further inquiries.

44-128—Telegraphy in the Bell System; J. A. Duncan, R. D. Parker (M'14), R. E. Pierce (M'30). 30 cents. As a part of the Morse centennial, this paper reviews some of the activities in telegraphy carried on by the various units of the Bell System in con-

nection with the furnishing of private-line telegraph and teletypewriter exchange service. At the present time approximately 4,000,000 miles of telegraph circuit facilities are used by the telephone companies, of which about 2,600,000 miles are obtained by carrier methods. Over 34,000 stations, most of which are teletypewriters, are served by these facilities. Frequent reference is made to publications covering developments and present activities. Only those items which have not been disclosed previously are covered in any detail.

44-129—Fundamentals of Hearing-Aid Design; *W. D. Penn (A'35). 20 cents.* Approximately four per cent of the population is sufficiently hard of hearing to require the use of a hearing aid. The nature of the hearing loss varies with the individual. From a knowledge of the characteristics of speech and hearing, the requirements a hearing aid must meet with respect to output, gain, and frequency response are determined. It is found that selective amplification is usually required. A novel method of obtaining the required type of selective amplification is described. The effect of room noise in limiting the maximum amplification which can be used is discussed. A method of computing the over-all acoustical gain is given. Performance curves of an instrument using the type of selective frequency control described are shown.

Domestic and Commercial Applications

44-154—Load-Calculation Procedure for Electric-Panel Space Heating; *B. F. Raber, F. W. Hutchinson. 30 cents.* Radiant heating by means of ceiling panels permits establishing comfort in a room with lower air temperature and with greater feeling of freshness of air than is possible with conventional heating systems. The paper presents three steps to be followed in designing panel-heating systems. These are of particular interest to the electrical engineer, because, as the paper explains, such systems seem to afford an effective means of improving the competitive position of electricity as a primary energy source for space heating. Aside from direct electric panels, the lower operating temperature of panels using any heating medium makes off-peak electrical thermal storage more practical, because of smaller equipment, than it is with conventional heating systems; over 250,000 kw of such systems are now in service. Of even greater promise is the possibility of utilizing low-temperature panels with a heat pump for all year conditioning, the lower winter surface temperature and higher summer surface temperature leading to an unusually high coefficient of performance.

44-155—Electrothermal Space Heating and Air Conditioning; *G. H. Krueger. 15 cents.* This paper will cover briefly a historical outline of space heating with a detailed description of the electrothermal off-peak method for space heating and air conditioning. The general principles involved in this method of heating are based on thermodynamic laws. Electrically generated heat energy is stored in hot water contained in a

vessel under 200-pounds-per-square-inch pressure at the saturated temperature of 388 degrees Fahrenheit. There is sufficient heat energy stored in the water in the pressure vessel to be liberated as steam into the heating system to supply the building's heating requirements during the peak periods. Therefore, nothing but off-peak energy is used to operate this system. The air conditioning operates on a closed cycle admitting only sufficient fresh air to maintain the proper oxygen and carbon dioxide contents in the air. It also operates at a slight positive pressure within the space to be heated thus preventing infiltration.

44-156—Possibilities of Heat Pumps for Heating Homes; *R. U. Berry (A'29). 15 cents.* Heat pumps are refrigerators in which the principal interest is in the heat output from the condenser. A few installations have been made in which the heat output is used for space heating, and there is a steadily growing interest in them. This paper deals briefly with their efficiency, fuel economy, and output characteristics in an average climate. Initial costs and operating costs are compared with those for fuel-burning systems, and estimates are given on the energy and demand requirements for an average residential system in a typical climate with equipment now available.

Electric Machinery

44-94—Evolution of Standard Lines of Current Transformers of High Overcurrent Capacity; *E. C. Wentz (M'42). 25 cents.* System-fault currents today are generally higher than they were years ago. The first current transformers built for high-current capacity were special designs. When more and more of them were required, the need to standardize the special designs became apparent. The theoretical basis of the new line of standard transformers is a thorough study of the electromagnetic forces produced by the high current. Formulas are developed for calculating these forces. Means for approximating the strengths of the windings against these forces are given and the theory is confirmed by tests to destruction on a number of transformers. The practical basis for the standardized transformers is a line of standard Hipersil cores designed to give uniform performance. A line of transformers is made for each core size for each value of fault current (associated with a standard circuit breaker).

44-103—Hot-Spot Temperatures in Dry-Type Transformer Windings; *H. C. Stewart (M'36), L. C. Whitman (A'39). 25 cents.* This paper gives the results of an extended series of thermal tests on a variety of dry-type transformer coils. Data are presented on the effect of different heights of coil stack, different configurations, and, in addition, some essential precautions in making temperature measurements are pointed out. Hot-spot temperatures were investigated in coils cooled by natural-draft and by forced-air circulation at different velocities for both directed flow and random flow. Hot-spot increments (hot-spot temperature minus average temperature) range from 11 degrees

centigrade for short natural-draft-cooled coils to 31 degrees centigrade for tall fan-cooled coils built with class A insulation (55 degrees centigrade) as contrasted with 10 degrees centigrade hot-spot allowance as given in American Standards Association, "Standards for Transformers, Regulators, and Reactors, C57.1, 1942" Hot-spot increments for class B insulation (80 degrees centigrade) vary from 16 to 46 degrees centigrade depending upon coil length and method of cooling. No hot-spot allowance has been established for class B insulation. The high hot-spot increments found in these tests show the need for review and modification of the standard allowances for dry-type transformers.

44-139—The Degree of Short-Circuit Protection Afforded Small Low-Voltage A-C and D-C Starters by Means of Fuses and Circuit Breakers; *B. W. Jones (M'43). 15 cents.* The AIEE technical paper 42-79 published in *Transactions*, volume 61, July 1942, pages 483-87, gave data regarding the interrupting ability of low-voltage cartridge-type fuses and their ability to protect small motor starters. These data were misinterpreted by some and it is the purpose of this article to point out the intended interpretation and to illustrate the main point with additional data.

44-140—Insulation Temperature Standards for Industrial-Control Coils; *B. W. Erikson. 15 cents.* It is proposed that higher temperature-rise values for industrial control coils be accepted by the industry, these higher values not to be applied indiscriminately to all designs, but to be used only in conjunction with:

1. Designs utilizing better than average class-A heat-resistant materials.
2. Coil constructions where the windings are compact and well supported.
3. Definitely only on circuits rated less than 600 volts.

This proposal is made because:

1. It will result in smaller and lighter designs and less electrical inertia and, therefore, faster contactor operation. The lighter weight also will promote longer life of the moving parts and over-all improved reliability.
2. Experience with many thousands of coils designed under the present National Electrical Manufacturers Association temperature limits over many years of service has been satisfactory.
3. Present day coils utilizing new synthetic insulating materials and improved methods of coil construction have superior life expectancy.
4. The small size, rigidity of construction, and relatively low voltage ratings, enable industrial-control coils to withstand temperatures higher than those permissible for many other applications. For instance, rotating machinery is usually conceded to be far more severe on the insulation system as compared with industrial-control service.

44-141—Industrial Control: Shunted-Armature Connection for a D-C Shunt Motor; *G. F. Leland, L. T. Rader (M'43). 15 cents.* This paper describes the shunted-armature connection used with a d-c shunt motor to obtain speed-torque control. Putting resistance in parallel with the armature, in addition to series line resistance, results in a method of obtaining slow-down control with good speed regulation at low initial cost. A simple graphical method is presented for obtaining the required values of shunt and series resistance to give two speci-

field speed-torque points. An analytical proof of the method also is included.

44-169—Progress in Impulse Testing of Transformers; *J. H. Hagenguth (M'44).* 30 cents. The paper describes briefly the test circuit and test procedure for impulse testing of transformers. The methods of failure detection and the complexity of the impulse test are discussed on the basis of experience gained in making design and commercial impulse tests on several million kilovolt-amperes of transformers. Experience has shown that not all failures can be detected with present methods. The best and most reliable method available at present is the direct comparison by superposition of cathode-ray oscillograms. Normal frequency excitation, simultaneously applied with the impulse, has been found inconclusive as a failure indicator. It not only increases testing time, but also requires protection practices which are apt to obscure failures. A new method of failure detection is described which is capable of detecting failure of one turn in 1,350 turns. This method should prove very useful as an accurate failure indicator.

44-171—The Design and Operating Characteristics of Modern Dry-Type Air-Cooled Transformers; *W. W. Satterlee (M'47).* 15 cents. This paper describes and discusses modern dry-type air-cooled transformers which are constructed with class-B insulation and combinations of organic and inorganic materials. These transformers will operate satisfactorily at relatively high winding temperatures because their insulation structure is designed and arranged to use basically inorganic materials where temperatures in excess of 130 degrees centigrade are attained. The results of tests and operating records show that the effects of humidity are unimportant and that overloads in excess of 150 per cent of rated load may be carried for long periods of time without detrimentally affecting the electrical and mechanical properties of these transformers.

44-174—Interlamination Resistance; *J. P. Barton (A'30).* 15 cents. In laminated core structures for transformers and rotating machines, the need for adequate interlamination resistance becomes more necessary as the core structures increase in size. A method for determination of the minimum interlamination resistance required in terms of the core and its operating conditions, for any degree of stray loss, is developed, resulting in a simple equation. A typical application of the equation is illustrated. The desirability of quality control of the interlamination resistance of finished laminations is reviewed by stating the need for measurement of the resistance at maximum operating temperature, pressure, and stray loss voltage in the core structure to assure adequate insulation of the lamination.

44-175—Transient Performance of Induction Motors; *F. J. Maginniss (A'43), N. R. Schultz (A'40).* 25 cents. This paper presents the results of a differential-analyzer study of the equations of induction-motor performance. The effects of rotor mechanical load and inertia are included in the analysis. Specific solutions are shown for a number of cases including full-voltage starting, plugging,

voltage dip, and short circuits, with emphasis placed on the transient motor torque and current obtained. Comparisons are made between the steady-state and transient speed-torque characteristics.

44-176—Differential Leakage With Respect to the Fundamental Wave and to the Harmonics—Integral-Slot and Squirrel-Cage Windings; *M. M. Liuschitz (M'39).* 30 cents. The standard theories of differential leakage do not consider the damping of this leakage by the currents induced in the secondary winding. They fail entirely when applied to the harmonics. A calculation of the parasitic torques and forces produced by the harmonics in induction motors and salient-pole synchronous machines is not possible on the basis of the standard theories of differential leakage. The object of this paper is to derive formulas for the differential leakage of integral-slot as well as fractional-slot windings taking into account the influence of damping, number of slots of stator and rotor, fractional pitch, and skewing. Special attention is paid also to the slot openings which in machines with open slots influence very considerably the slot harmonics. Curves are given which make it possible to calculate the differential leakage in a simple way. The integral-slot and squirrel-cage windings are treated.

44-177—The Nature of Vibration in Electric Machinery; *T. D. Graybeal (A'38).* 20 cents. Vibration in electric machinery is the result of a number of contributing agencies, some mechanical, others electromagnetic in origin. Features of mechanical and electrical design and construction which give rise to these agencies are discussed. The general character of the vibration which each agency produces is explained, as well as how different agencies combine to produce the resultant machine vibration. Where excessive vibration is encountered in the field, methods are outlined for ascertaining the major agencies responsible, so that corrective modifications may be made which will be effective in reducing the resultant vibration. These methods are applied to motor generator sets driven by two-pole induction motors to ascertain the cause of a particular type of vibration characterized by the vibration amplitude increasing and decreasing in uniform cycles twice during each revolution of motor slip. In this way the agencies which give rise to this particular type of vibration and how they may be controlled to keep the resultant vibration to a satisfactory minimum are explained.

44-170—High-Voltage Compressed-Gas Power Transformers; *H. M. Hobart (F'12).* 15 cents. Proposals made at various times by H. J. Ryan, P. N. Nunn, A. A. Boelsterli, H. H. Skilling, and others, and important original suggestions of colleagues, notably W. W. Lewis and G. B. Warren, have been fitted together in the present paper into a high-voltage compressed-gas system which embodies features required by the modern needs of the electric-power industry. Of such is the provision, without incurring fire hazard, of the great economies of load-center operation at indoor locations in industrial plants. The system also provides decreased

weights and costs of power transformers in general as well as longer life and greater capacity for sustained overloads. The proportion of the cost of transmission systems which is represented by the transformer outlay would be lessened very considerably by the employment of designs for higher periodicities of 600 cycles or more. Such periodicities cannot be used in long-distance overhead transmission lines because of corona, but it is proposed to associate the use of high periodicity with transmission conductors located in underground pipe lines containing a suitable gas at such a compression as to raise adequately the ionization limit. By means of such a system, using voltages greater than would be practicable with overhead lines and also using some such periodicity as 600 cycles, stable transmission can be provided for greater amounts of power than heretofore and for transmission over greater distances.

Electric Welding

44-101—Rating of Electric Equipment Under Intermittent Load; *Myron Zucker (M'36).* 25 cents. The duty-cycle method customarily used in rating resistance-welding equipment for intermittent load is satisfactory for some applications, but leaves much to be desired in logic and frequently in accuracy. For a given piece of apparatus it can be justified only under continuous repetition of fast cycles. Usually, however, cycles are long or are broken up into groups. Then use of "duty cycle" as a guide sometimes overloads equipment and sometimes calls for excess capacity—which means unnecessary investment and higher costs. This paper studies ratings under a wide range of periodic heating cycles and explains how the rather arbitrary "maximum averaging time" limit may be removed. It derives relations for long and for short cycles, for a limited number of repeats, and for continuous application. In short, it provides a straightforward method for finding the temperatures reached within equipment that is carrying periodic load. Tests on an interleaved low-voltage resistance-welding cable substantiate this analysis.

44-105—The Design of Low-Voltage Welding-Power Distribution; *C. A. Adams (F'13), J. R. Fletcher (A'36), A. C. Johnson (A'42).* 30 cents. This paper is an effort to state clearly, and to present a solution for, the problems encountered in the design of one of the vital constituents of a-c resistance-welder power supply—the low-voltage feeder. The scope of the paper is much wider, however, since the determination of design loads from the probability standpoint for the purpose of determining maximum allowable impedance and expected temperature rise, is a problem encountered in the design of all equipment common to a number of resistance-welding installations. The topics considered in the paper are:

1. Definition of voltage regulation as it applies to resistance-welding equipment.
2. Establishment of a criterion of good voltage regulation as defined.
3. Application of the theory of probability to the determination of maximum tolerable impedance and minimum copper section consistent with safe operating temperature.

4. Calculation of reactance of the closely spaced rectangular bar-bus-type feeder, which the authors believe is best suited for the job, and its nearest competitor for low reactance, the concentric tubular feeder.

5. Calculation of maximum current capacity in terms of allowable temperature rise in the aforementioned type of bus feeders.

6. Determination of force between conductors in flat bar bus under short-circuit conditions.

44-125—An Improved Electronic Control for Capacitor-Discharge Resistance Welding; *H. J. Bichsel (A'43), E. T. Hughes. 25 cents.* The resistance welding of aluminum has become exceedingly important during the past four years. Aluminum is difficult to spot-weld because of its narrow plastic range and high thermal conductivity. However, the capacitor-discharge welding system is capable of welding aluminum on a production basis because the energy delivered to each weld is controlled closely. This paper describes an electronic control for a capacitor-discharge welding machine which incorporates a new type of discharge circuit, an electronic flux resetting system to prevent saturation of the welding transformer, and a minimum number of relays so that high-speed operation and low maintenance cost can be obtained.

Electrochemistry and Electrometallurgy

44-99—Voltage Transients in Arc-Furnace Circuits; *AIEE subcommittee on transient voltages in arc-furnace circuits. 20 cents.* The AIEE subcommittee on voltage transients in arc-furnace circuits was established four years ago to study field and laboratory data. This paper summarizes field data accumulated and made available to the committee. Information regarding the transformer size, rated temperature rise, connections, voltage rating, and method of furnace grounding is tabulated with the system characteristics and magnitude of voltage transients recorded. Charts are included to show that there is little, if any, correlation between magnitude of the transients and transformer size or voltage rating. One chart compares the magnitude of transients experienced with the insulation levels of apparatus. A review of the data leads to the conclusion that the magnitude of voltage transients on the supply side of the transformer is generally comparable to that of switching surges occurring on power systems, but that the frequency of occurrence is very much greater. Preliminary recommendations for further work, and for adequate insulation levels and protective devices are made.

44-100—Treatment and Casting of Metals by Electromagnetic Forces; *W. W. Hoke. 20 cents.* Metals are treated and cast by forces unidirectionally obtained by the action of field on current in the molten metal. Impurity elimination is improved considerably by these forces which increase the buoyancy of the metal on the impurities by adding to the forces of gravity. Other effects of the treatment are a type of agitation effectively overcoming viscosity and a temperature gradient enabling progressive solidification in the direction of impurity elimination. In casting, the metal is rendered extremely sensitive to displacement into the mold. A greater complexity of casting is made possible with a minimum of casting pressure.

44-163—The Copper-Oxide Rectifier in Electrochemical Work; *I. R. Smith (A'43). 20 cents.* Electrochemical applications are among the oldest in which the copper-oxide rectifier has been used. They include battery charging of all types, cathodic protection of pipe lines, corrosion protection for water tanks, anodizing, and electroplating. Requirements in these fields are described and examples of typical rectifiers for these uses shown. Of special interest is a totally enclosed type of rectifier of 30-kw capacity, for electroplating. Information is given as to performance and life of both disk-and-plate-type rectifiers. Short discussions are included on basic rectifying-element characteristics, unit construction, and the manner in which ratings are established. Circuits commonly used for metallic rectifiers are illustrated and briefly described.

44-164—Electronic Regulator for Arc Furnaces; *J. E. Reilly (A'41), C. E. Valentine (M'41). 15 cents.* With the increased use of arc furnaces in the production of alloy steel, new interest has been aroused in both old and new methods of automatic regulation of electrode position. The regulator described in this paper is an electronic type which controls electrode position as determined by response to current in the electrode and voltage between the electrode and the furnace shell. Features and performance of an installation for a furnace having hydraulic control are illustrated.

44-165—Characteristics of Chlorinated Impregnants in D-C Paper Capacitors; *L. J. Berberich (M'36), C. V. Fields (A'41), R. E. Marbury (M'36). 25 cents.* D-c capacitors of the impregnated paper type play an important role in electronics equipment required by the armed services. Some of these applications require good performance over very wide temperature ranges. A new chlorinated hydrocarbon composition which maintains reasonable capacitance constancy over a wide temperature range is described. The properties of this liquid are compared with older chlorinated impregnants. Since some alternating voltages usually accompany the direct voltages applied to capacitors, the a-c behavior over wide temperature and frequency ranges is described for capacitors impregnated with three different liquids. The effect of voltage and temperature on the resistance of capacitors is discussed. Considerable attention is devoted to the life behavior of capacitors impregnated with chlorinated liquids under d-c stresses at high temperatures. A life testing procedure is described which has yielded very satisfactory results on capacitors of varying sizes and ratings. A means involving the addition of stabilizers for prolonging the life of capacitors impregnated with chlorinated impregnants is discussed. Data showing the effect of a number of stabilizers are presented. Finally, some data are presented showing the effect of voltage on the life of d-c capacitors.

44-166—Induction Heating—Selection of Frequency; *N. R. Stansel (M'35). 20 cents.* Induction heating is the use of eddy currents to raise the temperature of a conducting mass. An assembly for induction heating is a form of transformer. The equations of the circuits of this transformer are given (without derivations) in an appendix. The rela-

tion of frequency and the kilovolt-ampere capacity of this assembly is considered as the basis for the selection of the frequency for a given induction-heating service. The conclusion is that there is no optimum frequency for heating a charge to a temperature below the melting point of the material. However, there is an optimum range of frequency for each assembly of this kind. The induction furnace for melting metals is a special application of induction heating for which 960 cycles is standard practice for units above 100 kva.

44-167—ACO—Application of Industrial Radio-Frequency Generators to Induction Heating; *E. H. Browning (A'43). 15 cents.* Heating metals by means of magnetic induction is not a newly discovered art, but the war has done much to foster its rapid development in industry. This paper gives in part a brief presentation of the theory and practice of induction heating with particular emphasis placed on the ranges of frequencies obtainable and employed. Of the various types of electric equipment commercially available for the induction heating of metals, vacuum-tube oscillators are the most recent to make their entrance into industry. The paper discusses the application of radio-frequency generators to industrial induction-heating work and points out the types of heating best accomplished by the use of such equipment. Attention is directed to the factors involved in the installation, operation, and maintenance of radio-frequency generators in an attempt to show that such equipment is easily operated and sufficiently substantial to permit its use under most conditions met with in industrial plants.

44-168—Surface Heating by Induction; *H. F. Storm (A'42). 25 cents.* The heating effect by induction has been analyzed previously by means of partial differential equations whose solution are Bessel functions. It is the object of this paper to analyze the induction-heating effect by using concepts commonly applied to a-c engineering without employing differential equations. It was found that ordinary vector diagrams lead to quantitative expressions regarding the penetration of the magnetic field into the charge, the distribution of eddy currents and the generation of heat, as well as the impedance of the loaded inductor. The analysis is limited to the heating of a body of cylindrical shape, surrounded by a uniform alternating magnetic field.

Electronics

44-11—Analysis of Rectifier Circuits; *E. F. Christensen (A'39), C. H. Willis (F'42), C. C. Herskind (M'40). 30 cents.* This paper presents a standard procedure for the analysis of rectifier circuits. While the general principles underlying the analysis of rectifier circuits have been covered quite fully in the literature, there is not available a complete analysis giving the essential formulas in a systematic and unified form readily usable by engineers. It is the object of this paper to present such a treatment. The paper describes the methods used in determining the wave forms throughout the rectifier circuit and in deriving the mathematical formulas which apply. While the analysis is made for

the widely used delta double-wye circuit, the method is generalized so that it may be applied to all types of rectifier circuits. Rectifier-circuit calculations and presentation of calculated data are facilitated by expressing the various characteristics in terms of the reactance factor. A comprehensive set of characteristic curves expressing the various quantities in terms of reactance factor is included. These curves should prove useful to design, application, and operating engineers.

44-143—History and Development of the Electronic Power Converter; *E. F. W. Alexanderson (F'20), E. L. Phillipi. 15 cents.* The paper describes the evolution of the electronic converter from the mercury-arc rectifier. Mercury-arc tubes are subject to electronic faults which may develop into short circuits unless the situation is understood correctly. In the electronic converter we have, however, new means for controlling the power flow and suppressing the effect of faults so that they are of no practical consequence. Three types of electronic converters are described and their use for such purposes as power transmission by direct current, non-synchronous links between a-c systems, frequency converters, operation of a-c motors at variable speed, and transformation of direct current from high-voltage transmission to low-voltage motor circuits. The development of the electronic converter has, by making a virtue of a necessity, led to a new point of view in dealing with system faults.

44-145—Design of an Electronic Frequency Changer; *C. H. Willis (F'42), R. W. Kuenning (A'42), E. F. Christensen (A'39), B. D. Bedford (M'43). 25 cents.* The apparatus and design of a 20,000-kw electronic frequency changer, for interchanging power between a 44-kv 25-cycle system and a 69-kv 60-cycle system is described. The power circuit includes the main transformers, current-limiting reactors, tube cubicles, and d-c link. The station consists of two 10,000 units displaced 15 degrees to give 24-phase operation for the total station. A discussion of rectifier operation indicates phase-angle control of the rectifier grids to establish the desired load and inverter grid control to maintain the margin angle required for deionization. Grid and ignitor power is supplied from a phase-shift network operated by d-c saturated reactors. The phase angle is controlled by an Amplidyne which furnishes the saturating current for the reactors. Recovery from rectifier and inverter faults is obtained by electronic means without opening any power circuits and with only momentary loss of power.

44-147—Pentode Ignitrons for Electronic Power Converters; *H. C. Steiner (A'32), J. L. Zehner (Application Pending), H. E. Zuvers (A'43). 25 cents.* The name "pentode ignitron" has been applied to a high-voltage tube used for rectification and inversion in electronic converters. It is a sealed steel tube having an anode, three grids, and a mercury-pool cathode. The tube is of the gas-filled type with control characteristics similar to those of the thyatron. An ignitor establishes a cathode spot at each cycle on the mercury pool. The cathode spot is stabilized at low anode currents by the use of an

auxiliary holding anode. The functions of the three grids are somewhat similar to those in the pentode vacuum tube, but the manner of use is quite different. The first grid, or one nearest the anode, is used as an intermediate anode to divide potential gradients across the tube during nonconducting periods. The second, or center grid, is used to control the starting of the conduction period; and the third, or outer grid, as a shield to permit rapid deionization of the space between the control and shield grids. The introduction of multiple grids in ignitron tubes provides certain characteristics which are essential to inverter operation. It is the purpose of this paper to describe some of these characteristics and the design and construction of the pentode ignitron tube. These tubes are the ones installed in the power converter described in the companion papers: 44-143, 44-144, 44-145, and 44-146.

44-160—Operation of Rectifiers Under Unbalanced Conditions; *E. F. Christensen (A'39), M. M. Morack (M'42). 15 cents.* A multiphase mercury-arc rectifier and its associated transformer is designed so that, under normal conditions, the currents in all circuit elements will be balanced and there will be no d-c components of flux in the transformer core. Occasionally unbalanced anode currents obtain when, for instance, an anode is misfiring or entirely out of service. When the rectifier equipment is operated on less than normal anode complement, however, the circuit is no longer symmetrical and the remaining anodes do not share the d-c load current equally. Under this condition a d-c component of flux exists in the transformer core, and the interphase transformer is affected adversely by unbalanced currents in the two halves. This paper describes the distribution of currents in the various transformer windings and electric valves under various conditions of unbalance and determines the effect of such unbalances on the rated load capacity of rectifier equipment.

Industrial Power Applications

44-144—The Electronic Converter for Exchange of Power; *F. W. Cramer (M'40), L. W. Morton (A'38), A. G. Darling (Application Pending). 30 cents.* A 20,000-kw electronic power converter to exchange power, reversibly, between the 25-cycle 44-kv and the 60-cycle 69-kv systems of the Carnegie-Illinois Steel Company went into operation in December 1943. Installed in two 10,000-kw complete converters, both have met their overload rating of 200 per cent for one minute and 125 per cent for two hours. One unit even carried 125 per cent load for two weeks. The electronic converter output is held to a constant power output independently of relative system frequencies and voltages and may be reversed by selection of control circuits. It contributes no current to faults in the supply system—little more than load current to receiving-system faults while controls suppress power flow to internal faults. Switching is resorted to only for persistent faults. Reactive overexcited current must be supplied by synchronous apparatus of both systems, excess losses of which are chargeable to the converter. Efficiencies remain high throughout the load range.

44-146—Switchgear and Control for Electronic Power Converter; *W. N. Gittings (Application Pending), A. W. Baleman. 15 cents.* To the switchgear designer whose point of view is influenced so largely by the needs of the "man who operates and maintains" the electronic frequency converter presents some new and interesting opportunities. The ease with which the converter is switched into and out of service and its output is controlled presents the opportunity of providing simple and at the same time versatile controls by means of which the operator can make the fullest use of the converter in meeting the varying demands of his system. The peculiar and advantageous behavior of the electronic converter under system fault conditions permits the use of simpler system protective relays than are required when other types of converter are used. The inherent ability of the converter to recover from the more common internal faults presents new but somewhat simplified problems in the application of relays for protection from internal faults.

44-173—Application and Description of Automatic Control and Switching Equipment for Capacitor Banks; *T. W. Schroeder (M'44), W. C. Bloomquist (A'43). 20 cents.* The use, in increasing amounts, of shunt capacitors for voltage improvement, power-factor correction, and release of circuit capacity by utilities and their industrial customers, is leading in many cases to the desirability of automatically switching or controlling the capacitors. This paper describes standardized switching equipment and control to permit automatic switch of capacitors, in single or multiple steps, as a function of voltage, current, kilovars, or power factor. A line of equipment is described which covers the size and voltage range of capacitor banks employed by industrials and utilities. In addition to a detailed description of equipment and its operation, a discussion of the reasons for switching capacitors automatically is given; depending on the principal use that is made of the capacitors (for example, voltage or power-factor control) it is shown when they should be switched and which of several alternative methods of switching is most applicable.

44-178—Extending the Use of Shunt Capacitors By Means of Automatic Switching; *W. H. Cuttino (A'44). 20 cents.* It is generally recognized that the kilowatt loading on distribution circuits or plant feeders may be increased substantially by using capacitors to supply the kilovar load and relieve the current-carrying system of this burden. The use of capacitors to boost voltage or actually to regulate voltage has increased during recent years. Automatic switching of capacitors makes it possible to obtain the benefits of adding capacitors to take care of the full load kilovars without the objection of excess capacitor kilovars at light loads. It not only makes it possible to apply capacitors in the most effective manner from the standpoint of meeting power-factor limits established by the utility, but also provides a means of regulating voltage in the plant or on the system. Capacitors may be switched automatically by the same switching means controlling the load, or they may be switched in response to changes in circuit conditions such as voltage, current flowing, or the in-

ductive kilovars drawn by the load. The advantages of the various types of control and the choice of the number and size of capacitor steps to be switched are fully discussed.

Instruments and Measurements

44-161—A Resonant-Cavity Method for Measuring Dielectric Properties at Ultra-high Frequencies; *C. N. Works (A'40), T. W. Dakin, F. W. Boggs. 25 cents.* A re-entrant cylindrical cavity has been adapted to measure the dielectric constant and power factor of small disk samples of insulating materials. The disk of dielectric is placed between the flat ends of the cylindrical posts which form the re-entrant part of the cavity. The circuit is analogous to a less than one-quarter wave-length section of air-filled coaxial transmission line shorted at one end and ending in a capacitor with dielectric at the other end. This cavity with the dielectric inserted is brought to resonance by tuning the frequency of a loosely coupled oscillator. The power factor of the dielectric is determined from the breadth of the resonance curve, and the dielectric constant is obtained by removing the disk of dielectric and decreasing by a measured amount the separation of the flat ends of the re-entrant posts until resonance again is obtained at the same frequency as previously. The precision differential screw for varying the extension of the re-entrant post and other mechanical details are described. Electrical coupling and detecting methods also are discussed as well as the theory of the measurements. Each individual cavity can be utilized only over a frequency range of about 1.5 ratio from lowest to highest frequency. Therefore, several different-sized cavities would be required to cover a range of frequency from 50 to 1,000 megacycles. An accuracy of ± 0.00005 in $\tan \delta$ and ± 1 per cent in dielectric constant may be obtained in routine measurements. Because the cavity has a very high $Q (> 2,000)$, it is much more sensitive to low-power-factor dielectric samples than any conventional coil and capacitor resonant circuit. Operation of the apparatus is simple and rapid and very similar to the susceptance variation technique now used at lower radio frequencies.

Land Transportation

44-92—Modern Motive Power for Sorocabana Railway; *R. L. Chapman (M'30), O. K. Kjolseth. 15 cents.* The 20 electric locomotives being furnished to the Sorocabana Railway are the largest and most powerful 3,000-volt d-c meter-gauge units built to date. They weigh 286,000 pounds with 238,000 pounds on drivers, have a continuous rating of 1,910 horsepower, and will handle passenger, freight, and mixed trains on the 87-mile double-track mountainous section between São Paulo and Santo Antonio at a scheduled speed of 35 miles per hour for passenger, and 30 miles per hour for freight and mixed trains. The running gear consists of two three-axle driving trucks, and two single-axle radius bar guiding trucks. The truck frame, cab underframe, and cab are of welded construction, and incorporate throughout the use of fabricated subassemblies. The six traction motors are built to

operate two in series on 3,000 volts and are of the commutating-pole force-ventilated type with antifriction bearings. Axle-suspension bearings are waste-packed and oil-lubricated. Single reduction gearing is used. A total of nine running steps in motoring is obtained by series, parallel, and reduced field combinations. Regenerative braking also is provided. The locomotives have two operating positions—one in each end.

44-96—Economics of Trolley-Coach Operation; *G. M. Woods (M'43). 15 cents.* The trolley coach is receiving considerable attention in the field of city transit as a result of its ability to increase patronage and operate at low cost. Its proper field of economic application lies between the fields of the street car and the motor bus. There are now 3,500 trolley coaches in operation in the United States and Canada. In 1943 they carried 8.7 per cent of all transit passengers. In the past 15 years many improvements have been made in the design of the electrical equipment of trolley coaches and in the overhead line material. These improvements have contributed to economy of operation and to the quality of the service. Material extensions of trolley coach service in the postwar period now are being planned by properties which have broad experience in their operation.

Marine Transportation

44-142—Modern Cargo-Winch Control for Use on Victory Ships; *F. H. Holt. 20 cents.* After discussion of the operating characteristics required for the electric driven cargo winch, the manner in which these characteristics may be obtained by the use of a properly designed motor control is outlined. The power circuit used for each operating point and the reason for its use is given as well as such interesting features of the control circuit as the explanation of the means by which both rapid acceleration of a load and smooth deceleration of a load from high speed may be obtained. The problems encountered in incorporating the control equipment in a waterproof enclosure mounted on the side of the winch are explained. The design and testing of the ventilated resistor located in the waterproof enclosure and the method of selection of the thermal switch to protect the resistor are reviewed.

44-159—Fault Protection on Shipboard A-C Power-Distribution Systems; *H. G. Rickover (Application pending), P. N. Ross. 30 cents.* Because of the upward trend in electric-power requirements on shipboard and the consequent growth in size, importance, and complexity of the power system, the application of fault protective devices has become a major factor in designing shipboard power-distribution systems. In particular, greater emphasis must be placed on the analysis of switching transients, fault currents, and the co-ordination of the various protective devices to ensure adequate protection combined with maximum reliability and continuity of service. Conventional methods of securing fault protection on low-voltage a-c systems have a number of shortcomings in meeting the requirements of marine service. Particularly outstanding in this respect are the

limited usefulness of relays and the fact that oil-film time-delay dashpots commonly provided on low-voltage air circuit breakers are incapable of providing selective operation under fault conditions. A new direct-acting circuit breaker overcurrent trip device having characteristics suitable for fault protection on shipboard is described in the paper together with the principles and methods involved in the application of protective devices and calculation of fault currents.

Power Generation

44-98—The Summation of Load Curves; *R. F. Hamilton (M'18). 25 cents.* Wartime conditions offer engineers a challenge to utilize equipment to the utmost and to rearrange capacities according to needs. Peacetime economic controls no longer govern. This paper develops methods for computing load; the addition of loads which are similar except for timing; the addition of loads with various load factors; probability elements as applied to consumers' habits; the effect of peak time-concentration and load changes on the coincidence factor and system peaks; demand factors for composite loads including those for military establishments. Mathematical formulas are developed from fundamental elements of load curves and applied to typical problems.

44-106—The Effect of Weather on the System Load; *H. A. Dryar (M'43). 30 cents.* An accurate estimate of the daily peak load is essential to the reliable and efficient operation of an electric system. Daily peak variations usually reflect weather conditions. If any phase of the weather is excluded from the estimate, there may be a deficit in the operating capacity scheduled. The system load usually has two components. One, a fixed quantity, reflects business activity. The other, a variable quantity, the effect of weather. Correctly weighting this variable quantity promotes greater accuracy in load estimating. Occasionally another component indicates public response to broadcasts of unusual interest. This differentiation aids in assessing unusual load variations and determining their cause. To supplement the official weather forecast, existing weather conditions are weighted by the load dispatcher two hours before peak time and a final estimate made. If there is an error in the load estimate, its cause probably will be immediately apparent in changing weather conditions.

44-107—Conditions Controlling the Economic Selection of Prime Movers; *B. G. A. Skrotzki. 30 cents.* This paper attempts to clarify the effect of various controlling conditions on the magnitude of the evaluation constants used to select the optimum prime mover to be added to a system with a growing load. A hypothetical load has been set up which is assumed to grow at a known constant rate. By fixing on a policy of equal-sized units with two units being installed reserve and one unit operating reserve regardless of load magnitude, the progress of the individual generating units from the base to the top of the load curve can be studied readily. With the fundamental mechanics of the problem delineated the effects of unit availability, unit life span, rate of load

growth, load cycle, load factor, unit capacity, and system reserve policy are analyzed. From this analysis certain principles are apparent. Among the most important are:

1. Historical data of past and present prime mover experience are of very limited value.
2. Evaluation constants for future prime movers are not fixed in magnitude and must be redetermined from time to time for each individual system.

Having demonstrated the relative importance of the various controlling conditions this work concludes with a recommended procedure for determining the evaluation constants for any practical case.

Power Transmission and Distribution

44-114—The Measurement of Lightning Currents in Direct Strokes; *G. D. McCann (M '44). 20 cents.* The magnitude and wave shape of the discharge currents from 46 direct strokes have been measured during a five-year period at 25 direct-stroke recording stations on structures ranging in height from 75 to 585 feet. Measurements have been made with instruments capable of recording the wave front and tail of the high-current peaks and the low-magnitude continuing currents to as low as 0.1 ampere. Photographs have been made with special lightning cameras of 138 strokes to open ground and 22 cloud-to-cloud discharges. Data are given on the frequency with which objects of various heights are struck by lightning and the effect of height upon the character of the discharge. The principal characteristics of the lightning currents are summarized and several unusual recorded conditions are noted. Probability curves are given on the range and frequency of occurrence of the various stroke characteristics including polarity, total charge, crest current, wave front, time to half value, and duration.

44-115—Transmission - Line Electric Loadings; *S. B. Crary (M '37). 25 cents.* The electrical loading of transmission lines depends upon many factors worthy of review. Transmission systems by the use of quick switching, relaying, and modern design practices have overcome their stability limitations to a very considerable extent. This progress indicates the possibility of further increasing transmission-line loadings. This paper is devoted to discussion of real and reactive losses and stability limits of transmission lines from 50 to 300 miles in length, with a rather complete discussion of the characteristics of the 100-mile line which was taken as an important representative length for the transmission interconnections now existing. The real and reactive and their incremental losses are given in terms of dimensionless quantities which are applicable for lines of any length and voltage. Low resistance conductors are shown to have additional advantages beyond that of reduced real power losses, such as increased stability limit, reduced reactive kilovolt-amperes required for transmission, and a more equal distribution of the reactive kilovolt-amperes requirements between sending and receiving ends.

44-116—Ring Buses for Generating and Transmission Stations; *E. L. Michelson (A '37), J. P. Galassini (A '38). 20 cents.*

Changes in bus requirements have led to the adoption of the ring bus as the standard bus installation in the generating and distributing stations of a large midwestern power system. The first bus layouts in this power system employed the straight-line bus but, because of changes in the methods of system operation, improved quality of equipment, and other requirements, the ring bus was found to have certain desirable features. The paper describes the electrical connections and the operating characteristics for the various forms of the straight-line bus and ring bus. It shows why it is advantageous to use the ring bus from the viewpoints of

1. Flexibility of connections.
2. Ease of providing relay protection.
3. Simplicity of maintenance.
4. Economy in investment.

This paper also contains the results of studies investigating the application of the ring bus to high-voltage transmission terminals.

44-117—Capacitor Installation at Newport News; *V. R. Parrack (M '37), E. L. Harder (M '47). 25 cents.* To meet a predicted reactive load requirement of approximately 15,000 kilovars, a large capacitor bank was installed at Newport News. This paper outlines the considerations involved in selecting the static capacitor and determining its novel design features. The 10,500-volt capacitor bank was made up of low-voltage outdoor pole-type units which could be used later in the distribution system. It was divided into five sections with manual switching for control of voltage. Tests were made after installation to check the adequacy and operating characteristics of the installation with regard to regulation, inrush currents, voltages during switching, and effect on wave shape. The underlying theories of these phenomena are reviewed briefly in the paper to provide a background for interpretation of the various test results presented. Tables, curves, and formulas for predicting inrush current magnitudes and frequencies and voltages encountered during switching are given. In general, the tests verified the ability to predict the several performance characteristics and provided useful empirical data on regulation. Inrush currents and voltages during switching were well within the limits of proper application. Harmonics were not seriously increased. The positive results of these tests provide a satisfying bench mark on the road to larger capacitor installations in single banks.

44-118—Capacitors, Condensers, and System Stability; *J. W. Butler (M '38), T. W. Schroeder (M '44), W. Ridgway (A '47). 30 cents.* This paper reports a study comparing the performance from the stability standpoint of a system using a large capacitor bank with that of the same system using a synchronous condenser of the same rating at the same location. Two general types of systems were studied, the so-called "interconnected" and the isolated or "noninterconnected." For the noninterconnected system, the effects on the transient stability of the hydroelectric station inertia, transient reactance, fault-clearing times, and so forth, are determined for either type of kilovar source of various ratings (condenser or capacitor) located at the receiving end. The

effect on steady-state stability of supplying kilovars in the load areas is also determined. For the interconnected system, the effects on the transient-stability limits of the relative sizes of the two systems and the fault-clearing times, for either type and rating of intermediate kilovar source, are determined. The steady-state limits are also investigated. In general, it is shown that the difference between the effects on transient and steady-state stability of large capacitor banks and synchronous condensers is small.

44-119—A Method of Approach to the Consideration of Power-Distribution-System Costs; *O. B. Falls, Jr. (A '39). 20 cents.* The purpose of this paper is to present a generalized method of approach to the consideration of power-distribution system costs for various combinations of conditions when considering collectively the costs of each of the three basic elements which make up the so-called distribution system. These elements are:

1. The subtransmission circuits supplying the distribution substations.
2. The substations which transform from the subtransmission to the primary voltage.
3. The primary distribution system.

It has been found that consideration of the cost of any one of these parts without reference to the others may lead to erroneous conclusions as to the best over-all system from a cost standpoint. That is, the use of the minimum-cost design for one part may require expenditures for the other parts resulting in an over-all system cost higher than that necessary if all parts had been reviewed jointly and designs evaluated on an over-all basis. This kind of approach, wherein all elements of the system are included, is believed to be one which will give a complete picture of system costs.

44-130—Impulse Strength of Insulated-Power-Cable Circuits; *Herman Halperin (M '26), G. B. Shanklin (M '29). 30 cents.* This paper has been prepared at the request of the cable working group, AIEE committee on power transmission and distribution, to form an engineering basis for coordinating cable circuits with other equipment with regard to their ability to withstand transient overvoltages. Recommendations are given for safe withstand-impulse voltage of cables and accessories of various types. These are derived from co-ordinated analysis of all available published and unpublished data as well as some new test results. The significance of this information is discussed from the standpoint of overvoltages due to lightning and switching to determine when protective measures are necessary. Standard methods of impulse tests on cables are recommended.

44-131—Cyclic Movement of Cable—Its Causes and Effects on Cable Sheath Life; *C. S. Schifreen (M '43). 30 cents.* The relationships between loading, conductor-temperature changes, movement in manholes and ducts, and sheath life of paper and lead cable are discussed on the bases of operating experience, field surveys, and laboratory tests. The paper evaluates the factors re-

sponsible for the large percentage of non-inherent failures attributable to the physical proportions of underground structures on a large mileage of 15-kv three-conductor belted cable. The tests and operating experience indicate that unsatisfactory sheath life can result from daily cyclic movement of cable, although it may be operating at temperatures allowed in standard cable specifications. Modern paper insulation can withstand these temperatures safely as reflected in the relatively few inherent failures. Snaking of cable in ducts may impose severe cyclic strains and become the determining factor for optimum sheath life. Based on these tests, a method was developed for computing sheath life for given cable offsets and movements at the duct mouth.

44-132—An Investigation of the Relationship Between Temperature and Movement of Cables in Ducts; C. T. Nicholson, T. J. Brosnan (M'34). 15 cents. This paper describes the field tests which were made to determine the relationship between cable temperatures and cable movement in the manholes in an underground cable installation in Buffalo, N. Y. The special equipment and the testing procedure are described, and the test measurements are given in the paper. The results of the tests indicate that, in the area where the tests were made and for average cable section lengths, the practical operating factor is about one millimeter of realized longitudinal expansion per degree centigrade increase in sheath temperature. The test results suggest an explanation of how the cable expansion develops during temperature changes from different causes.

44-133—Gas-Filled Cable Research and Experience; G. B. Shanklin (M'29). 15 cents. Operating experience for the past five years with low, medium, and high-pressure gas-filled-cable installations is briefly outlined. Research and test data on gas-filled cable are presented and analyzed. Initial ionization starting voltage as a function of gas pressure ranging from atmospheric to 225 pounds per square inch, is compared with theoretical results and the significance of this starting voltage as related to practical gas-filled-cable design is explained. Long-time load-cycle endurance tests on gas-filled cable, covering a wide range of impregnating-compound viscosities, are presented, and the self-grading and self-healing properties of gas-filled cable are shown to be related to the viscosity of the impregnating compound. These beneficial properties increase in efficiency with decrease in viscosity, and the corresponding increase in mobility of the impregnating compound as a result of the compound's being drawn into voids and other critical locations by the electrical stress field. An optimum range of compound viscosities for best all-around results is demonstrated.

44-134—Operation of Low-Pressure Gas-Filled Cable; C. T. Hatcher (M'37). 15 cents. In papers presented before the AIEE in 1939 and subsequent years the theoretical aspects of paper-insulated cable utilizing gas as a pressure medium were discussed. Extensive laboratory test data were presented indicating the expected life of this type of

cable. This paper presents factual data on the actual operation of low-pressure gas-filled cable of various types on the system of a large utility. The operating record for five years is presented and appears to substantiate previous laboratory data. The paper is the most comprehensive treatment of the subject pertaining to operating problems and experience yet published.

Protective Devices

44-93—Current-Transformer Output and Application Charts; R. Köller (A'43). 15 cents. In recent years a great deal of effort has been spent on the simplification of characteristic curves for multiratio bushing-type current transformers for relaying service. This paper describes a simplified chart from which the ratio error can be determined for any value of primary current, any number of secondary turns, and any value of secondary burden. The volt-ampere output of bushing-type current transformers at low primary currents is small and, in order to obtain optimum performance of relays, careful tuning between transformer taps and secondary burden is required. The volt-ampere-output characteristics are analyzed and a simple application chart is developed for tuning of relays and transformers. The use of the chart is explained in connection with various examples applied to commonly used relaying circuits.

44-97—Fusing Practices on Distribution Systems—II; J. S. Parsons (A'27), J. M. Wallace (A'47). 15 cents. Part I, recently presented, described the fusing practices now in use on about 150 systems operating below 5 kv. The present paper contains data gathered from the same operating companies on systems between 5 and 15 kv. Transformer fusing practice is tabulated for different circuit conditions. Charts showing the minimum size fuse link used and the maximum number of sectionalizing fuses also are given.

44-102—A Pneumatic Mechanism for Outdoor Oil Circuit Breakers; L. J. Linde (A'39), E. B. Rietz (A'42). 15 cents. The power required to operate the contacts of a circuit breaker is a function of its operating speed. The high operating speeds of modern tank-type oil circuit breakers often demand power beyond the capacity of existing control power sources. This power demand may be reduced very considerably if energy storage is used at a circuit breaker location. This paper describes the use of such stored energy in a compressed-air pneumatically trip-free mechanism for outdoor oil circuit breakers. Its simple design and low power demands add to its reliability and simplify the problems of application. Alternative methods of energy accumulation are discussed and the operating characteristics of the more usual prime movers for circuit breaker operators are briefly compared.

44-104—Bibliography of Relay Literature, 1940-43; Interim report by the working group of the relay subcommittee of the AIEE committee on protective devices. 30 cents. This report lists all important articles on the subject of protective

relaying published from 1940 to 1943 inclusive in the AIEE *Transactions* and *Electrical Engineering* as well as most of the chief publications of the world. Previously this report has been available only to the members of the relay subcommittee in annual reports and to the general public only at ten-year intervals. However, the consensus of the subcommittee was that the urgency of the relay problems brought about by the war emergency makes it desirable to have this information more generally available at the present time. This report will supplement the paper, "Bibliography of Relay Literature, 1927 to 1939," published in July 1941 by the Institute.

44-135—A New Carrier Relaying System; T. R. Halman (M'43), S. L. Goldsborough (M'43), H. W. Lensner (A'43), A. F. Drompp. 15 cents. The many advantages of a single relay for complete phase and ground-fault protection of a transmission line have been realized in modern pilot-wire relays. By using the same basic principle of comparing single-phase quantities proportional to currents at the two ends of a line and using power-line carrier instead of a pilot wire, a new relaying system has been developed which combines the simplicity of pilot-wire protection with the versatility of carrier. An electronic trigger circuit is employed to provide half-cycle pulses of carrier-frequency energy from both ends of the line. These pulses are received at the opposite ends and compared with the phase position of the local single-phase quantity to determine whether an internal or external fault exists. An intermittent carrier system is used so that the carrier channel is available for auxiliary functions. Laboratory and field tests have proved the dependability of the new system.

44-157—Protection of Large D-C Rotating Machines by Means of High-Speed Circuit Breakers; J. E. Housley (F'43), Otto Jensen (A'47). 15 cents. A high-speed circuit breaker has been developed for the protection of large installations of d-c rotating machines. The circuit breaker is rated 7,500 continuous amperes and its contacts separated in 0.25 cycle (60-cycle basis). Short-circuit conditions of various d-c systems are described. The breaker utilizes a bucking-bar-holding-type magnet in combination with a roller clutch for its high-speed operation. The breaker and the modernization of a large rotary-converter station are described in detail.

44-158—Improved Selective Tripping of Low-Voltage Air Circuit Breakers; C. P. West (M'28). 15 cents. Selective tripping of low-voltage interrupting devices has been a problem since the first applications in which they were used in series. Arrangements, similar to those commonly used with high-voltage breakers, in which all interrupting devices have adequate interrupting ratings and selective opening is obtained by protective relays and by shunt-trip coils are best for insuring maximum continuity of power to all loads. However, this may require breakers which are relatively expensive compared with the power-consuming apparatus which they supply. Special cascaded arrangements defined by the National Electrical Manu-

facturers Association permit the use of low-voltage breakers in certain parts of circuits where they may be subjected to fault currents above their interrupting rating. But this use of less expensive breakers imposes a more restricted interrupting duty cycle and more maintenance is to be expected. Fully selective tripping for isolating breakers in cascaded circuits is not possible as main and group breakers must be allowed to open instantaneously if the current in the breaker next lower in the cascade exceeds its interrupting rating. This means a partial sacrifice of continuity of power to normal circuits. New integral mechanically delayed tripping devices for low-voltage breakers soon will be available. They will have nearly constant time-current tripping characteristics between the minimum and instantaneous operating values. This will improve the selective tripping of breakers in cascade circuits as back-up breakers can be kept closed safely until the current exceeds the interrupting capacity of the breaker next lower in the cascade. Delayed tripping at lower currents for selective action is provided. These tripping devices applied in circuits where all breakers have full interrupting capacity and short time ratings will give selective tripping equivalent to that now provided by shunt-trip coils and protective relays.

44-172—A New Frequency Relay for Power-System Applications; *J. L. Blackburn (M'44), H. J. Carlin (A'47).* 20 cents. Applications of frequency relays to power systems are described in which the relays are used to disconnect loads or system ties during emergencies. The requirements of the frequency relays for these applications are analyzed and a new relay which satisfies these requirements is described. This relay has adjustable time delay and a wide range of frequency settings with minimum temperature and voltage error.

Quality Control

44-113-ACO—The Applications of Statistics to Dielectrics; *C. M. Summers (M'39), K. E. Ross.* 15 cents. The application of statistics to insulations brings forth three important engineering problems which, heretofore, have not been given the consideration they deserve.

1. The specifications for a material must define adequately the characteristics of the insulating material.
2. A method of evaluating the material must be formulated to assure both the supplier and user that the material agrees with the specifications.
3. The material specifications must be translated into design practice.

The value of statistical terms and methods used in establishing a specification is stressed and control charts are suggested for determining whether or not the material adheres to the specifications. Illustrations based on the electrical and mechanical properties of an insulation paper are used. The transformation from a material specification to design practice and test objectives takes into consideration the time and temperature elements which affect the breakdown of insulation material. The use of statistical methods for determining the factors of safety is considered.

PERSONAL

J. W. White (A'29) vice-president and general manager, Westinghouse Electric International Company, New York, N. Y., has been elected president and general manager. Mr. White first was employed by the Westinghouse Electric and Manufacturing Company, in Pittsburgh, Pa., Detroit, Mich., and Chicago, Ill., as sales engineer from 1907 to 1918. In 1918 he went to Havana, Cuba, as manager for the Westinghouse International Company. He was made general manager of the Westinghouse Company of Japan, Tokyo, in 1925 and managing director in 1927. From 1931 to 1936 he was stationed in Buenos Aires, Argentina, as managing director of the South American company. In 1936 he was appointed general manager and in 1937 vice-president. **G. H. Bucher (M'24)** formerly president of the International company, becomes chairman of the board. Mr. Bucher is also president of the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa. He was elected president of the International company in 1932 and president in 1934. He assisted in organizing the Westinghouse Electric Company of Japan in 1925.

Howard Maxwell (A'03, M'35) manager of the induction motor department, General Electric Company, Schenectady, N. Y., has retired. Graduating from the University of Kansas in 1900, he entered the General Electric Company as student engineer and in 1903 was transferred to the a-c engineering department. Entering the induction motor department in 1913 as superintendent he was made managing engineer in 1914 and manager in 1918. **M. H. Wells (A'12)** engineer in the induction motor department also has retired. Mr. Wells a graduate of Syracuse University entered the company as student engineer in 1902. In 1903 he became engineer in the a-c engineering department and in 1918 was named design engineer in the induction motor department.

M. M. Kenneally (M'29) formerly vice-president and sales manager, Porcelain Insulator Corporation, Lima, N. Y., is now associated with Joslyn Manufacturing Company. He also will act as special representative for the Porcelain Insulator Corporation.

R. L. Bertolacci (A'19) recently connected with the Federal Power Commission, Washington, D. C., is now on the electrical engineering staff of the California Railroad Commission, Los Angeles, with which he was associated as assistant engineer in 1934 and 1935.

J. S. Murray (A'21, M'31) chief electrical engineer, Follansbee (W. Va.) Steel Corporation, has been elected second vice-president of the Association of Iron and Steel Engineers for 1944. Mr. Murray held the office of national treasurer of that association in 1943.

L. J. Westin (A'35) formerly assistant manager of the boiler department, Day and Zimmermann, Inc., Philadelphia, Pa., has received the commission of lieutenant,

junior grade, in the United States Naval Reserve, Ordnance Division.

W. L. Hiscox (M'35) formerly of the long lines engineering department, American Telephone and Telegraph Company, New York, N. Y., has been transferred to the general staff of the operating and engineering department.

W. R. Whitney (A'01) vice-president in charge of research, General Electric Company, Schenectady, N. Y., has been made an honorary member of the Electrochemical Society. Doctor Whitney was Edison medalist and John Fritz medalist for 1943.

R. H. Ranger (M'22) formerly major, Signal Corps, United States Army, has been promoted to lieutenant colonel and is now chief of the Corps' standards activities branch, Red Bank, N. J.

C. A. Atherton (M'42) formerly commercial engineer, Champion Lamp Works, Lynn, Mass., is on the staff of the development engineering department of the Reynolds Metals Company, Louisville, Ky.

G. S. Timoshenko (A'33, M'39) associate professor of electrical engineering, University of Connecticut, Storrs, is engaged in research development for the Templetone Radio Company, Mystic, Conn.

H. W. Neblett (A'15, M'21) development and new design engineer, Inland Steel Company, East Chicago, Ind., has been elected a director of the Association of Iron and Steel Engineers for 1944.

R. E. Doherty (A'16, F'39) president of the Carnegie Institute of Technology, Pittsburgh, Pa., has been elected honorary member of the Engineering Institute of Canada.

De Gaspe Beaubien (A'07, M'21) consulting engineer, De Gaspe Beaubien and Company, Montreal, Que., has been elected president of the Engineering Institute of Canada.

T. H. Hogg (M'31, F'38) chairman and chief engineer, Hydro-Electric Power Commission of Ontario, Toronto, has been appointed to represent Canada on the public utilities committee of the United Nations.

C. T. Hurd (A'37) formerly salesman, Allis-Chalmers Manufacturing Company, Seattle, Wash., has been named central station specialist. Mr. Hurd has been employed by the company since 1935.

A. F. Duernberger (A'40) formerly commander in the United States Naval Reserve has been promoted to the rank of captain and is the commanding officer of the Naval Training School, Iowa State College, Ames.

J. W. Barker (M'26, F'30) dean, faculty of engineering, and professor of electrical engineering, Columbia University, New York, N. Y., recently received the honorary degree of doctor of laws from Union College.

J. H. Hagenguth (A'28, M'44) electrical engineer, General Electric Company, Schenectady, N. Y., has been appointed a member of the American Standard Association's committee on sphere gap standards.

W. P. Bear (M'22) retired engineer, Pacific Gas and Electric Company, San Francisco,

Calif., now is affiliated with the United States Maritime Commission, Oakland, Calif.

H. P. Liversidge (A '12, F '43) president, Philadelphia (Pa.) Electric Company recently was honored with the degree of doctor of science by Drexel Institute of Technology.

J. W. Gore (A '41) formerly foreman, electrical department, Bethlehem Steel Company, Baltimore, Md., has been made electrical superintendent.

R. C. Young (A '29) formerly sales engineer, Kuhlman Electric Company, Bay City, Mich., has been appointed assistant sales manager.

M. L. Waring (A '29, M '36) formerly captain, ordnance department, United States Army, is now a major.

OBITUARY

George Wilbur Hubley (A '94, M '00, F '26) consulting engineer, Louisville, Ky., died April 8, 1944. Born in Pittsburgh, Pa., May 9, 1870, he commenced his career in the student course of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1887. In 1890 he became construction superintendent for the Citizens Traction Company, Pittsburgh. From 1893 to 1915 he was superintendent and chief engineer of the Louisville Gas and Electric Company and from 1915 to 1918 general manager and chief engineer of the Mechanics Heat and Light Company, Indianapolis, Ind. He was fuel administrative engineer in Louisville for the United States Fuel Administration in 1918. Since 1919 he had carried on a consulting practice in Louisville. He served as engineer with the Public Utilities Bureau of the City of Louisville from 1923 to 1935 and consulting engineer for the State Board of Charities and Correction from 1920 to 1924. He was a member of the American Society of Mechanical Engineers, the American Gas Association, the Sons of the American Revolution, and the Louisville Board of Trade.

Harry Gardner Wood (A '23, M '28) electrical engineer, Worthington Pump and Machinery Corporation, Harrison, N. J., died April 4, 1944. Mr. Wood, who was born August 2, 1891, in Jacksonville, Ill., received the degree of bachelor of science in electrical engineering from the University of Illinois in 1914. He entered the graduate student course of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1914 and in 1915 was transferred to the switchboard section. He was made switchboard expert for the company's New York (N. Y.) District office, in 1916 and except for 17 months service with the United States Army remained in that position until in 1922 he was placed in charge of the switchboard section. He was named consulting engineer in 1923 and district engineer in 1927. In 1931 he joined the electrical sales department of the Worthington Pump company as consultant. He was a member of the Electrical Association of New York.

H. W. Hough (A '08, M '13) vice-president and general manager, Cleveland (Ohio) Electric Illuminating Company died recently. Mr. Hough was born January 20, 1885, in Baltimore, Md., and entered the electrical field in 1902 when he was employed by the Consolidated Gas and Electric Light and Power Company, Baltimore, for which he did testing, drafting, construction, and substation layout. From 1907 to 1910 he was chief electrician for the Norfolk (Va.) and Southern Railroad. In 1910 he joined the Cleveland Electric Illuminating Company and was made assistant to the chief electrical engineer in 1914. After a period of service as captain in the Engineers Corps of the United States Army, he returned to the company in 1919 as research engineer. He was appointed assistant to the president in 1923 and associate general manager in 1930. In 1934 he became vice-president and general manager.

Maxwell Henry (M '32) associate professor of electrical engineering, school of technology, College of the City of New York, N. Y., died April 7, 1944. Born in New York City, December 26, 1897, Professor Henry was graduated from the College of the City of New York in 1924 with the degree of bachelor of science. He had obtained a master electrician's license in 1918. In 1924 he was appointed instructor in electrical engineering at the College of the City of New York and was made assistant professor in 1930. In 1940 he became associate professor. He was a consultant for the New York State Civil Service Commission and one of the designers of the new Hunter College and Queens College buildings in New York City.

Victor Emmanuel Northup (A '39) superintendent of distribution and transmission, Scranton, (Pa.) Electric Company, died February 4, 1944. He was born November 20, 1888, in Glenburn, Pa. He worked as oiler and switchboard operator for the Atlantic City (N. J.) Electric Company in 1906 and 1907 before joining the Scranton Electric Company in 1907 as turbine and switchboard operator. He became substation operator in 1908 and meter tester in 1909. He served as district representative for the company at Archbald, Pa., from 1910 to 1912 and in 1912 was made service inspector and field engineer. He was appointed distribution and transmission engineer in 1922 and superintendent of distribution and transmission in 1929.

Edwin Richter Pearson (A '06, M '12) retired electrical engineer, Portsmouth, N. H., died recently. Mr. Pearson was born February 6, 1863, in Portsmouth, and was graduated from Massachusetts Institute of Technology in 1888. He was associated with the General Electric Company throughout his engineering career. He was employed as engineer in the transformer department in Lynn, Mass., from 1890 to 1895 and in Schenectady, N. Y., from 1895 to 1908. Transferred to Pittsfield, Mass., in 1909, he continued in the transformer department. In 1917 he was named consulting engineer and in 1922 he returned to Schenectady as electrical engineer. He retired in 1934.

J. B. Smith (A '24, M '33) assistant superintendent of electric production, Southern Indiana Gas and Electric Company, Evansville, died recently. Born in Glasgow, Scotland, October 21, 1893, Mr. Smith attended the West of Scotland Technical College. After serving in World War I, he was made electrical engineer in charge of station and distribution, Cia. de Electricidad, Punta Arenas, Chile. From 1922 to 1924 he represented Henley's Telegraph Works, Company, Ltd., London, England, as electrical sales engineer in Mexico. He entered the employ of the Central Illinois Light and Power Company, Peoria, in 1924 and joined the Southern Indiana Gas and Electric Company in 1928.

MEMBERSHIP . .

Recommended for Transfer

The board of examiners, at its meeting on May 18, 1944, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Allen, T. H., president, Board of Light, Gas and Water Commissioners, Memphis, Tenn.
Chandler, R. B., general mgr., Port Arthur Public Utilities Commission, Port Arthur, Ont., Canada
Giroux, C. H., special asst. to chief of engineers, U. S. War Dept., Washington, D. C.
Knight, Norman, chief engineer, western area, Bell Telephone Co. of Canada, Toronto, Ont., Canada
Lewis, F. M., senior engineer, U. S. Army Engineers, Bonneville, Oregon
Lindsay, R. W., vice-president, Mountain States Tel. & Tel. Co., Denver, Colo.
McCormack, J. E., asst. outside plant engr., Consolidated Edison Co. of N. Y., Inc., New York
Reid, C. R., general supt., Shawinigan Water & Power Co., Montreal, Que., Canada
Starbird, L. C., transmission and protection engr. for Texas, Southwestern Bell Telephone Co., Dallas, Texas
Wulff, H. E., system planning engr., Commonwealth Edison Co., Chicago, Ill.

10 to grade of Fellow

To Grade of Member

Allen, W. M., Engr., Pacific Tel. & Tel. Co., Portland, Ore.
Ashmead, H. E., electrical engr., Naval Ordnance Lab., Washington, D. C.
Auld, W. F., chief engr., Lincoln Electric Co. of Canada, Ltd., Leaside, Ont., Canada
Bastedo, E. H., contract elec. engr., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
Bement, D. L., vice-president, Northern Indiana Public Service Co., Hammond, Ind.
Blaize, L. J., asst. to vice-president, Dallas Power & Light Co., Dallas, Texas
Boesen, P. J., traction engr., City of Chicago, Chicago, Ill.
Buchanan, H. F., application engr., General Electric Co., Chicago, Ill.
Butterworth, P. T., division head, Boston Edison Co., Boston, Mass.
Chapin, S. L., elec. engr., Sargent & Lundy, Chicago, Ill.
Clark, W. R., electrical research engr., Leeds & Northrup Co., Philadelphia, Pa.
Cogbill, B. A., designing engr., General Electric Co., Pittsfield, Mass.
Colvin, A. D., transmission engr., Southwestern Bell Telephone Co., Dallas, Texas
Crosby, P. W., senior engr., Philadelphia Electric Co., Philadelphia, Pa.
Curtis, A. E., asst. supt. of transmission lines, The Shawinigan Water & Power Co., Montreal, Que.
Delvin, R. B., chief of technical staff, United Shipyards, Ltd., Montreal, Que., Canada
Dunn, J. F., associate elec. engr., Tennessee Valley Authority, Knoxville, Tenn.
Ein, Sam, engr., Carnegie Illinois Steel Corp., Chicago, Ill.
Elliott, R. D., chief engr., Dallas Power & Light Co., Dallas, Texas
Erbe, J. R., steel mill and metal working engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.
Exner, D. W., design engr., Westinghouse E. & M. Co., Lima, Ohio
Frigon, Augustin, acting general mgr., Canadian Broadcasting Corp., Montreal, Que., Canada
Galassini, J. P., planning engr., Commonwealth Edison Co., Chicago, Ill.

Core, C. W., chief engr., Clark & Wilson Lumber Co., Portland, Ore.
 Jore, J. W., supt., elec. dept., Bethlehem Steel Co., Baltimore, Md.
 Hampe, G. W., engr., Commonwealth Edison Co., Chicago, Ill.
 Harris, Thomas, owner, H. S. Tittle Co., San Francisco, Calif.
 Holder, Edward, supt. of metering, Shawinigan Water & Power Co., Montreal, Que., Can.
 Jones, C. W., asst. elec. design engr., New England Power Service Co., Boston, Mass.
 Jones, T. B., Lieut., U. S. Naval Reserve, Chicago, Ill.
 Jones, T. L., plant extension engr., Southwestern Bell Tel. Co., St. Louis, Mo.
 Knapp, E. W., system planning engr., Shawinigan Water & Power Co., Montreal, Que., Canada
 Laneto, J. W., engg. dept., Hartford Electric Light Co., Hartford, Conn.
 Martin, H. L., NW District Central Station Mgr., Westinghouse E. & M. Co., Chicago, Ill.
 McDonald, D. J., foreign wire relations engr., Bell Tel. Co. of Canada, Montreal, Que., Canada
 Michelson, E. L., supervising planning engr., Commonwealth Edison Co., Chicago, Ill.
 Millington, J. W., research engr., Sun Oil Co., Beaumont, Texas
 Morgan, N. L., cable design engr., Northern Electric Co., Ltd., Montreal, Que., Canada
 Nixon, J. A., engr., Southern New England Tel. Co., New Haven, Conn.
 Price, G. F., engr., Southeastern Underwriters Association, Atlanta, Ga.
 Ringer, R. L., elec. engr., Allen B. DuMont Labs., Inc., Passaic, N. J.
 Robison, H. H., asst. regional utility engr., War Production Board, Dallas, Texas
 Shaw, H. N., consulting engr., Eric, Pa.
 Sellers, L. R., senior elec. engr., Tennessee Valley Authority, Knoxville, Tenn.
 Steever, R. G. E., engr., General Electric Service Shop, Dallas, Texas
 Vencill, G. J., hydraulic engr., Union Electric Co. of Missouri, St. Louis, Mo.
 Webb, R. B., engr., Southwestern Bell Tel. Co., Dallas, Texas
 Whaley, C. D., elec. engr., Sperry Gyroscope Co., Inc., Garden City, N. Y.
 Wilson, H. R., Lieut., U. S. Naval Reserve, Cambridge, Mass.
 Wolf, E. F., asst. to supt., Consolidated Gas Elec. Lt. & Pwr. Co., Baltimore, Md.
 Wright, J. L., industrial sales engr., General Electric Co., Portland, Ore.

51 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1944, or August 31, 1944, if the applicant resides outside of the United States or Canada.

To Grade of Member

Andrews, C. F., Ill. Northern Utilities Co., Dixon, Ill.
 Baker, F. J., Elec. Pr. Board of Chattanooga, Chattanooga, Tenn.
 Barnett, D. E., Memphis Light, Gas & Water Div., Memphis, Tenn.
 Cerrillo, M., Mexican Gov., Mexico, D. F., Mex.
 Clark, K. R., Austin Co., Cleveland, Ohio
 Dahms, A. A., Allis-Chalmers Mfg. Co., Kansas City, Mo.
 Dorsch, E. O., E. O. Dorsch Elec. Co., St. Louis, Mo.
 Eberhardt, W. W. (Reelection), Alabama Pr. Co., Birmingham, Ala.
 Elitgroth, G. V., Bendix Aviation Corp., Towson, Md.
 Fellows, F. C., H. Stevens Co., New York, N. Y.
 Fitch, L. C., General Elec. Co., Pittsfield, Mass.
 Gagen, J. M. (Reelection), Federal Pub. Housing Auth., New York, N. Y.
 Gunnison, G., C. H. Stevens Co., New York, N. Y.
 Havas, V., Austin Co., Cleveland, Ohio
 Hillemeier, A. K., Mississippi River Pr. Co., Keokuk, Iowa
 Johnson, K. C., Major, U. S. Army, Pine Bluff Arsenal, Ark.
 Kinn, T. P., Westinghouse Elec. & Mfg. Co., Baltimore, Md.
 Kline, C. M., Ajax Elec. Furnace Corp., Philadelphia, Pa.
 Kwasky, A. J., Hurley Marine Works, Oakland, Calif.
 Leavitt, A. J. (Reelection), Metcalf & Eddy, Engrs., Boston, Mass.
 Leib, F. E. (Reelection), Copperweld Steel Co., Washington, D. C.
 Matzenauer, J. H., St. Bonaventure College, St. Bonaventure, N. Y.
 Mayo-Wells, W. J., British Air Comm., Washington, D. C.
 McCann, C. F., New York State Elec. & Gas Corp., Elmira, N. Y.
 Murphy, L. J. (Reelection), Westinghouse Elec. & Mfg. Co., Buffalo, N. Y.
 Norwood, R. F., Chesapeake & Potomac Tel. Co. of W. Va., Charleston, W. Va.
 Peterson, E. S., Jr., J. A. Jones Const. Co., Brunswick, Ga.
 Potts, W. R., Atlantic Steel Co., Atlanta, Ga.
 Prendergast, R. M. (Reelection), Canadian Gen. Elec. Co. Ltd., Ottawa, Ont., Can.

Ramsay, A. T. (Reelection), Southern Bell Tel. & Tel. Co., Atlanta, Ga.
 Rickover, H. G., Capt., U. S. Navy, Washington, D. C.
 Snow, D. P., Standard Tel. & Cables, Ltd., Leicester, England
 Rutherford, G. R. (Reelection), Southern Calif. Tel. Co., Los Angeles, Calif.
 Stapleton, G. M., Ward Leonard Elec. Co., Mount Vernon, N. Y.
 Strange, E. M., Boeing Aircraft Co., Seattle, Wash.
 Stremel, R. A., Yuba Mfg. Co., Benicia, Calif.
 Wright, H. R., Pacific Mills, Ltd., Ocean Falls, B. C., Can.

37 to grade of Member

To Grade of Associate

United States and Canada

1. NORTH EASTERN

Bronzo, J. A., Mass. Inst. of Tech., Cambridge, Mass.
 Cafora, T. P., Radio Center Service, Bridgeport, Conn.
 Collins, J. S., So. New Eng. Tel. Co., New Haven, Conn.
 Eck, F. E., General Elec. Co., Pittsfield, Mass.
 Fitch, W. M., Jr., General Elec. Co., Schenectady, N. Y.
 Gunnoe, H. G., Jr., General Elec. Co., Schenectady, N. Y.
 Howell, R. L., Central N. Y. Pr. Corp., Oswego, N. Y.
 Jones, C. L., Jr., Central N. Y. Pr. Co., Utica, N. Y.
 Lariton, V. C., Rudolph Wurlitzer Co., North Tonawanda, N. Y.
 Phillips, M. T., U. S. Engineers, Buffalo, N. Y.
 Priestley, K., Eastern Elec. Const. Co., Bridgeport, Conn.
 Redman, E. M., Stromberg-Carlson Co., Rochester, N. Y.
 Reifsnnyder, J. G., General Elec. Co., Schenectady, N. Y.
 Robbins, C. D., General Elec. Co., Schenectady, N. Y.
 Shere, G. L., Raytheon Mfg. Co., Waltham, Mass.
 Ward, J. T., Boston Edison Co., Boston, Mass.
 Zehner, J. L., General Elec. Co., Schenectady, N. Y.

2. MIDDLE EASTERN

Bailey, R. C., Ohio Bell Tel. Co., Youngstown, Ohio
 Debel, C. A., Naval Research Lab., Bellevue, D. C.
 Duryee, P. A., Fisher Aircraft Div., Cleveland, Ohio
 Dyer, C. E., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
 Feige, W. C., Jr., Cons. Gas Elec. Lt. & Pr. Co. of Balt., Baltimore, Md.
 Foland, M. E., National Cash Reg. Co., Dayton, Ohio
 Friedman, C., Ensign, USNR, Washington, D. C.
 Gregory, J. A., C & P Tel. Co. of Wash., D. C., Washington, D. C.
 Hemenway, C. A., Alliance Mfg. Co., Alliance, Ohio
 Jones, E. E., Naval Ordnance Lab., Washington, D. C.
 Kuester, D. W., Jr., U. S. Navy Yard, Washington, D. C.
 Nicolai, R. C., Fenn College, Cleveland, Ohio
 Olson, C. O., Jr., Naval Research Lab., Washington, D. C.
 Rife, W. M., National Cash Reg. Co., Dayton, Ohio
 Thaler, G. J., Johns Hopkins Univ., Baltimore, Md.
 Vilchis, C. C., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
 White, J. C., Penna. R.R., Wilmington, Del.

3. NEW YORK CITY

Andersen, C. J., Sanderson & Porter, New York, N. Y.
 Barnes, R. F., Kellogg Corp., New York, N. Y.
 Brittain, G. H., Jr., Hamilton Radio Corp., New York, N. Y.
 Hausle, F. T., Queens Borough Gas & Elec. Co., Far Rockaway, N. Y.
 Hoffman, J. S., General Elec. Co., New York, N. Y.
 Kuhn, A. H., M. W. Kellogg Co., New York, N. Y.
 Ledermann, F., Patent Attorney, New York, N. Y.
 Leach, P. H., Jr., Kellogg Corp., New York, N. Y.
 Lerner, M. L., Westinghouse Elec. & Mfg. Co., Newark, N. J.
 Lynn, F. L., Sperry Gyroscope Co., Lake Success, N. Y.
 Meier, J. C., "Electrical World," New York, N. Y.
 Neidig, F. J., North American Philips Co., New York, N. Y.
 Schooley, C. E., American Tel. & Tel. Co., New York, N. Y.
 Stenger, F. J., Columbia Univ. Airborne Instrument Lab., Mineola, N. Y.
 Weaver, D. E., Elec. Storage Battery Co., New York, N. Y.

4. SOUTHERN

Bloom, T., Norfolk Navy Yard, Portsmouth, Va.
 Elder, B. H., Ethyl-Dow Chemical Co., Wilmington, N. C.
 Hoagland, J. W., U. S. Navy, Louisville, Ky.
 Jones, G. L., Tenn. Eastman Corp., Oak Ridge, Tenn.
 Lanier, W. J., Allis-Chalmers Mfg. Co., Memphis, Tenn.
 Myers, C. S., Westinghouse Elec. & Mfg. Co., Atlanta, Ga.
 Nelson, R. E., Tenn. Eastman Corp., Oak Ridge, Tenn.
 Peltier, K. W., Tenn. Eastman Corp., Kingsport, Tenn.
 Pool, R. P. (Reelection), Tubize Rayon Corp., Rome, Ga.

5. GREAT LAKES

Adler, H. A., Commonwealth Edison Co., Chicago, Ill.
 Barnes, T. F., Detroit Edison Co., Detroit, Mich.
 Dammann, G. E. (Reelection), Commonwealth Edison Co., Chicago, Ill.
 Feigl, R. S., Minneapolis Honeywell Reg. Co., Minneapolis, Minn.
 Fitzgerald, J. S., Caterpillar Tractor Co., Peoria, Ill.
 Freer, J. E., Reo Motors, Inc., Lansing, Mich.
 Furst, U. R., Russell Elec. Co., Chicago, Ill.
 Hempstead, K. F., Pub. Serv. Co. of Northern Ill., Waukegan, Ill.
 Janssens, J. N., Intl. Automatic Elec. Corp., Chicago, Ill.

Kriz, A., Bureau of Engg., City of Chicago, Chicago, Ill.
 LeBron, R. L., Jr., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
 Liggett, C. P., Commercial Solvents Corp., Peoria, Ill.
 Lommen, R. M., Cutler-Hammer, Inc., Milwaukee, Wis.
 Neslon, L. N. (Reelection), General Elec. Co., Fort Wayne, Ind.
 Russell, L. T., Consumers Pr. Co., Jackson, Mich.
 Tongret, S., Radio Corp. of America, Indianapolis, Ind.
 Weinhold, R. D., Allis-Chalmers Mfg. Co., West Allis, Wis.

6. NORTH CENTRAL

Collier, J. E., Collier Elec. Co., Denver, Colo.
 Rempe, E. H., Mountain States Tel. & Tel. Co., Denver, Colo.
 Walters, E. T., U. S. Bur. of Reclamation, Seminole Dam, Wyo.

7. SOUTH WEST

Bliss, W. J. (Reelection), Square D Co., Houston, Texas
 Cardwell, L. H., Dallas Pr. & Lt. Co., Dallas, Texas
 Collerain, J. F., Sr., Houston Pipe Line Co., Houston, Texas
 Fewell, E. C., Union Elec. Co. of Mo., St. Louis, Mo.
 Jenkins, J. M., Curtiss-Wright Corp., St. Louis, Mo.
 Luckey, R. W., Electrical Post Engineer Office, Jefferson Barracks, Mo.
 Lyman, C. D., Kansas City Pr. & Lt. Co., Ottawa, Kans.
 Maas, G. A., General Elec. Co., Dallas, Texas
 Rademeyer, H. P., Curtiss-Wright Corp., St. Louis, Mo.
 Rembert, E. H., Pub. Serv. Co. of Okla., Tulsa, Okla.

8. PACIFIC

Chapel, F. G., Southern Calif. Tel. Co., Los Angeles, Calif.
 Cuning, J. C. (Reelection), Bureau of Pr. & Lt., Los Angeles, Calif.
 Derin, H. H., U. S. Navy, San Francisco, Calif.
 Ford, F. D., U. S. Naval Drydocks, Hunters Point, Calif.
 Jones, R. J., U. S. Navy Yard, Mare Island, Calif.
 Jurwich, C. C., Southern Calif. Tel. Co., Los Angeles, Calif.
 Schott, F. W., San Diego Gas & Elec. Co., San Diego, Calif.
 Walters, W. T., General Metals Corp., Oakland, Calif.

9. NORTH WEST

Bergdahl, G. R., E. I. DuPont de Nemours & Co., Richland, Wash.
 Bjork, R. E., Montana Pr. Co., Great Falls, Mont.
 Byers, E. C., Washington Water Pr. Co., Spokane, Wash.
 Chambliss, H. E. (Reelection), Montana Pr. Co., Great Falls, Mont.
 Daniels, C. C. (Reelection), Montana Pr. Co., Great Falls, Mont.
 Heineck, W. A., Washington Water Pr. Co., Spokane, Wash.
 McArthur, S. E., Montana Pr. Co., Great Falls, Mont.
 McGee, T. W., Boeing Aircraft Co., Seattle, Wash.
 Monroe, B. J., Montana Pr. Co., Great Falls, Mont.
 Morton, H. A., Montana Pr. Co., Great Falls, Mont.
 Neumann, W. R., Montana Pr. Co., Great Falls, Mont.
 Nordeen, B. W., Montana Pr. Co., Great Falls, Mont.
 Sheire, J. B., Montana Pr. Co., Great Falls, Mont.
 VanNoy, T. A., Montana Pr. Co., Great Falls, Mont.
 Wilson, R. M., Washington Water Pr. Co., Spokane, Wash.

10. CANADA

Armstrong, H. D., Lieut., R.C.N. V.R., Toronto, Ont., Can.
 Foulis, R. M., Dorval Airport, Dorval, Que., Can.
 Harris, R. A., Canada Wire & Cable Co., Ltd., Leaside, Ont., Can.
 Hogg, J. D., Montreal Engg. Co., Ltd., Montreal, Que., Can.
 Little, J. A., Commonwealth Elec. Corp., Ltd., Welland, Ont., Can.
 Orwell, A. E., Northern Elec. Co., Ltd., Montreal, Que., Can.

Elsewhere

Barrios-Morales F., D., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Carrion, A. A., National Rys. of Mex., Mexico, D. F., Mex.
 Chellappa, T. R., Pykara Elect. System, Coimbatore, Madras, India
 Elizondo N. A., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Garcia R., D. L., Mex. Gov. Defense Sec., Mexico, D. F., Mex.
 Gutierrez, S. F., National Powder Factory, Santa Fe, D. F., Mex.
 Kiewek, C. J., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Lerch G., E., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Liubere Z., P., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Loubet V., E., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Mata, E. R., Mex. de Electricidad, Mexico, D. F., Mex.
 Mayer O., C., CIA Mex. Maquinaria, Mexico, D. F., Mex.
 Monterrubio B., I., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Otero O., J. F., Com. Federal de Electricidad, Mexico, D. F., Mex.
 Peralta Diaz C., A., Ind. Unidas S. A., Mexico, D. F., Mex.
 Rivera S., J., Contracting & Consulting Engr., Mexico, D. F., Mex.

Total to grade of Associate
 United States and Canada 117
 Elsewhere 16

OF CURRENT INTEREST

Clearinghouse for Technical Translations Established

A technical-translations clearinghouse has been organized recently to supply a focal service for photoprinted copies of articles translated from foreign scientific journals or periodicals. It is being operated as an extension of the auxiliary publication service of the American Documentation Institute with the co-operation of the Office of Alien Property Custodian.

Provision for such a service was undertaken at the suggestion of interested organizations which offered copies of their translations as a nucleus. Scientists, libraries, and research and industrial organizations possessing technical translations published in whole or part since 1940 are asked to deposit with the clearinghouse a typed ribbon copy or a good carbon of each translation now on file or to be published in the future. If only one copy of the translation is in existence that copy should be deposited, and the ADI will replace this with a microfilm or photoprint as desired. The clearinghouse is also soliciting information concerning existing public, institutional, and commercially available collections of such translations which should include the location of the collection, general description of the contents and the name and address of the person from whom the material can be requested.

A complete list of translations available from both the technical-translations clearinghouse and other existing reference pools will be compiled shortly for wide distribution. In order to avoid possible infringement of foreign copyright interests, the Alien Property Custodian, within specified limits, will vest such copyright interests and license the reproductions of such translations for general use and distribution.

Copies of translations and information pertinent to their availability should be addressed to the American Documentation Institute, 1719 N Street North West, Washington, D. C. Translations will be supplied upon order at the standard ADI copying-cost rate of one cent per page in microfilm and ten cents per page in photoprint, with a minimum charge of 50 cents.

Technically Trained Personnel Urged to Register With NRSSP

The National Roster of Scientific and Specialized Personnel, a civilian agency of the Government created in 1940 as a central registry for persons possessing professional and scientific qualifications, is responsible for the best utilization for the war effort of technically trained personnel.

In the light of recent Selective Service directives that will result in the induction of many thousands of professionally and scientifically trained young men under the age of 26, it is important that all qualified young engineers, chemists, physicists, geologists, mathematicians, and others be so

registered. Those individuals who will enter the Armed Forces immediately should notify the Roster of the branch of service they are entering, the date and place of their induction, and, afterwards, their serial number.

Although the Roster has no responsibility as regards their assignment within the Armed Forces, it reports to the office of The Adjutant General, War Department, and to the Bureau of Navy Personnel, Navy Department, concerning the specialized training and qualifications of those of its registrants inducted into the Army or Navy. This information is used as an aid in determining the initial military assignment of the particular individual. Should it become necessary to withdraw a number of specialists from the Armed Forces in order to reassign them to important research or production work in civilian war industry, the Roster's records are sufficiently detailed to permit intelligent selection of qualified individuals in almost every specialized field, and probably it will be called upon to assist in any such assignment.

Initial registration or notice of any change in status should be addressed to the National Roster of Scientific and Specialized Personnel, 1006 U Street North West, Washington 25, D. C.

Inventors Council Poses Military Problems for Public Solution

The National Inventors Council has recently announced a new list of problems of present import to the armed services for which it is soliciting solutions. (For previous listing see *EE*, Aug. '43, p. 380). Included in the list are the following suggestions which may be of interest to electrical engineers:

1. A relatively simple gauge to measure the impulse of explosion blast. Its positive and negative phases should be determined separately but concurrently, and it would be desirable if the duration of each phase could be determined in some simple manner.
2. Removal of dissolved mineral matter from sea and brackish water by ionic-exchange process.
3. An instrument for the location and destruction of concealed enemy emplacements, pillboxes, and similar strong points.
4. Improvements in tank vision devices and control instruments. There is special interest in reducing space requirements and improving the performance of gyroscopic compasses.
5. Ingenious and simple decoy devices for the purpose of confusing and misleading the enemy.
6. Technical data as to strategic enemy targets such as chemical plants, explosive plants, power plants, and so forth.
7. A noiseless hand generator combined with a lightweight flashlight. The generator should be pumped at the rate of 40 revolutions per minute, and the light should start on the first pump and should be continuously brilliant.
8. Plumb bob type of generator to operate a light six-volt radio. The generator probably should be operated by a reel winding up and letting out the plumb bob.

Suggestions should be submitted to the National Inventors Council, Room 1313, Commerce Building, Washington 25, D. C.,

and should comprise a clear description of the proposal with such sketches or drawings as may be necessary.

Allis-Chalmers Creates New Division. Creation of a new research and gas-turbine development division of Allis-Chalmers Company, Milwaukee, Wis., under the management of J. T. Rettaliata, has been announced recently by R. C. Allen, manager of the company's steam-turbine department. Although all steam-turbine design and engineering-research activities will be conducted by the new division, its most significant work will be in the development of the much-discussed gas turbine. Previously the company has built nearly 30 gas-turbine units for oil refineries and currently is producing the aircraft supercharger version of the gas turbine. Doctor Rettaliata has specialized largely in gas-turbine research and development, and has received annual awards for the past three years from national engineering and scientific societies for his contributions to this field.

United States and Canadian Armed Forces Standardize Radio Tubes

To make possible interchangeability of tubes, common stockpiles, and use of standard nomenclature, and to eliminate dual inspection at manufacturers' plants, the United States Army and Navy and the Canadian armed services have authorized standardization of radio tubes, according to reports received from the Office of the Chief Signal Officer.

The recently approved specification for radio tubes is based on the use of Radio Manufacturers' Association and commercial type numbers, and derives from work begun early in 1942 by a joint Army-Navy committee. Before Pearl Harbor, each of the services had its own system of tube nomenclature which, in many cases, was unrelated to that of the RMA and other commercial type numbers. It is expected that the quality of the tubes will improve somewhat in the future, now that the manufacturer no longer is obliged to make the same type of tube meet slightly different specifications.

INDUSTRY.....

WGN Conducts \$10,000 Contest for Design of New Radio Theater

WGN, Inc., sponsors of the 720-kilocycle broadcasting station in Chicago, Ill., has announced a \$10,000 prize contest for the design of a new air theater capable of seating 2,000 persons, to be constructed as soon as materials are available. As projected, it will be adaptable to both television and FM

broadcasting, and will be constructed in the heart of a new eight- or ten-story building to be erected by WGN as a complement to the prizewinning design.

Prizes for the winning designs, to be awarded by a group of WGN radio experts, will be distributed as follows: \$5,000 for first prize, \$2,500 for second prize, \$1,000 for third prize, and 15 prizes of \$100 each. Basic principles on which the contest is to be judged are, in the order of their importance, acoustics and utility, visibility, and beauty of design.

The stage should be approximately 60 feet square and capable of accommodating an orchestra of 75 pieces, a chorus of 40, and the principals of a musical cast. It should be adaptable for dramatic performance, and should allow for control rooms, flyloft, lighting equipment, and storage space. The auditorium may have one or two balconies, at the discretion of the designer.

\$1,000 Annual Award Honoring Stanton Hertz Established

Creation of the Hertz Award, a tribute to Stanton S. Hertz (F '39) late vice-president and assistant to the president of the Copperweld Steel Company, Glassport, Pa., was announced at the annual convention of the National Rural Electric Co-operative Association held in Chicago, Ill., recently. It provides for a bequest in the amount of \$1,000 to be presented annually, with an appropriate medal, to the person employed by a member Co-operative who, in the opinion of the award committee, has made the greatest technical contribution to the field of rural overhead-line design, construction, or maintenance during the preceding year.

The award was established by the Copperweld Steel Company, with whom Mr. Hertz was affiliated for about eighteen years, to commemorate "his significant engineering contributions to the progress of rural electrification in the United States." It will be bestowed for the first time at the 1945 convention of the NRECA. Recommendations for the honor shall be made to the award committee by the presidents of the operating Rural Electric Co-operatives, and a majority vote of the committee's membership, not yet announced, will determine the recipient.

Mr. Hertz was well known to the electrical industry for his studies on grounding problems and electric conductors. He served from 1936-41 as the first executive director of the Copper-Wire Engineering Association, and was one of the pioneers in the development of Copperweld-copper conductors for rural electrification. He died on February 17, 1943. For a more detailed biographical sketch of Mr. Hertz, see *Electrical Engineering*, April 1943, page 176.

KYW, KDKA, and WBZ Plan Television Broadcasting. Applications for licenses to install television broadcasting facilities as additions to radio stations KYW in Philadelphia, Pa., WBZ in Boston, Mass., and KDKA in Pittsburgh, Pa., as soon as critical materials become available, have been filed with

the Federal Communications Commission by Westinghouse Radio Stations, Inc., L. B. Wailes, general manager of the company has announced. Establishment of the television stations will entail additions of new studios, transmitters, and other equipment to the company's radiobroadcasting stations in the three cities. The company is contemplating future televised programs of motion pictures and outdoor events as well as the existing studio shows. Television techniques and radio program sources are expected to lead naturally to broadening of the medium's usefulness.

Industry-University Research Project Established at Purdue

Establishment of a joint industry-education enterprise at Purdue University, Lafayette, Ind., for intensive training of graduate students in exploration of the field of heat transfer was announced recently by G. Stanley Meikle, research director of the Purdue Research Foundation, and A. A. Potter, dean of the Schools of Engineering.

Made possible by a \$75,000 grant from Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., the five-year training and research program will be directed by George A. Hawkins of the Purdue University engineering faculty, who has been appointed Westinghouse research professor in heat transfer. Dr. Hawkins will select his research associates, to be known as fellows, and for their experiments the scientists will have access to the heat-transfer laboratory of the school of mechanical and aeronautical engineering and other University facilities. Dr. Max Jakob of the Illinois Institute of Technology will co-operate with Dr. Hawkins in the capacity of nonresident research professor.

Dielectric-Heating Research Begun at Columbia and Illinois

Laboratories for research into the basic principles and industrial applications of high-frequency heating have been established at Columbia University, New York, N. Y., and the Illinois Institute of Technology, Chicago, with the aid and support of interested corporations.

The laboratory for investigating high-frequency heating at Columbia University will be staffed by chemical engineers from the University and by scientists and technical experts from the Induction Heating Corporation, New York, N. Y. which has equipped the laboratory. The research program is under the direction of Arthur W. Hixson, professor and head of the University's department of chemical engineering and Philip W. Shutz, professor of chemical engineering. Everett K. McMahon, specialist in chemical engineering applications is in charge of the laboratory.

A similar \$5,000 research project for the study of dielectric heating has been initiated at Illinois Institute of Technology, by the Chicago Molded Products Company. J. E. Hobson (M '41) head of the electrical-engineering department will supervise the electrical phase of the studies and E. J.

Bicek, instructor in chemistry, the chemical phase. Bernard Parmet (Enrolled Student) and Arthur Kott, research assistants in electrical engineering and chemistry, respectively, have been awarded fellowships to carry on the project.

Already successfully employed in the dehydration of foods and in the setting of glue between plywood layers, dielectric heating is expected to be applied widely in such processes as the drying of lumber, soap, and ceramic materials and in the curing of rubber and the molding of plastics. Although the cost is still prohibitive for everyday use, high-frequency heating has been employed experimentally in cooking.

Welding Industry Symposium Published.

"Welding Industry Symposium," a compilation of 23 technical papers covering diverse phases of welding, recently was issued by the Consolidated Reporting Company, New York, N. Y. Among the subjects discussed are welding techniques, safety and health, fundamental metallurgy, fabrication of tools by welding, repairing, and common welding problems.

M. E. Thompson Dies. M. E. Thompson, pioneer in the electrical industry and inventor, who helped develop the compensated generator, died April 5, 1944, in Ridgway, Pa. He was 80 years old. Mr. Thompson received the degree of bachelor of science from Cornell University in 1890. As assistant to Harris J. Ryan, professor of electrical engineering at Cornell University and later at Leland-Stanford University, he conducted tests on the first electric generator equipped with compensating windings, designed by Doctor Ryan. As a result of these tests Mr. Thompson designed in 1893 the ten-kilowatt 110-volt six-pole belted generator now displayed in the Edison Institute, Dearborn, Mich., which bears the inscription: "This is the first generator ever built having compensated winding and commutating poles." During World War I he was a pioneer in the development of electrical propulsion equipment for submarines of the United States Navy. Mr. Thompson previously had been chief engineer of the Elliott Company, Jeannette, Pa., and at the time of his death was employed by the company as consulting engineer. He was the oldest employee of the Ridgway division of the company.

OTHER SOCIETIES.

ASTM Forms Committee on Metal Powders and Their Products

A new standing committee on metal powders and metal-powder products, B-9, has been established by the American Society for Testing Materials to undertake the formulation of specifications and methods of tests for these materials. Technical representatives of leading producers and consumers of metal powders and their products are serving on the committee and its working groups,

with W. A. Reich, General Electric Company, Schenectady, N. Y., as chairman, and W. R. Toeplitz, production manager, Bound Brook (N. J.) Oilless Bearing Company as secretary.

Subcommittees, organized to consider immediately adequate tests and methods of evaluating essential properties of the powders and compacts, are listed with their chairman as follows:

1. *Nomenclature and technical data*: chairman; F. N. Rhines, Carnegie Institute of Technology, Pittsburgh, Pa.
2. *Metal powders*: chairman; D. O. Noel, Metals Disintegrating Company, Inc., Elizabeth, N. J.
3. *Metal-powder products*: chairman; R. P. Koehring, Moraine Products Division, General Motors Corporation Dayton, Ohio.

The new technical committee is an outgrowth of the symposium on powder metallurgy held in March 1943, and the great expansion in the use of powder-metal products.

National Electronics Conference To Meet in Chicago, Ill.

The first annual National Electronics Conference which is described as a "national forum for electronic developments and their engineering applications," will be held at the Medinah Club, Chicago, Ill., October 5-7, 1944.

Sponsored jointly by the Illinois Institute of Technology, Northwestern University, the Chicago section of the Institute of Radio Engineers, and the Chicago Section of the AIEE, the conference will provide a common meeting place for technical personnel interested in applications in the broad field of electronics. Particular attention is being given to the needs of the many industrial engineers who have used electronic methods in restricted and specialized applications. Technical papers and discussion groups are being planned to treat the communication, industrial, measurement, instrumentation, control, research, and medical applications of electronics. One session will be devoted to educational problems and an electronic curriculum for technical schools and colleges. A. B. Bronwell (A '34) assistant professor of electrical engineering, Northwestern University, Evanston, Ill., is chairman of the program committee and Beverly Dudley, 520 North Michigan Avenue, Chicago, Ill., is secretary.

Effect of Welding on Ductility Now Predetermined. A new system for predetermining the loss of ductility in the base metal adjacent to a weld is proposed in a recent publication of the American Welding Society, "Guide to Weldability of Steels." Once a design and a welding process for

Future Meetings of Other Societies

American Society for Testing Materials. 47th annual meeting, June 26-30, 1944, New York, N. Y.

American Society of Civil Engineers. July 16-21, 1944, Chicago, Ill.

American Society of Mechanical Engineers. Semi-annual meeting, June 19-20, 1944, Pittsburgh, Pa.

Fall meeting, October 2-5, 1944, Cincinnati, Ohio.

Canadian Electrical Association. Annual meeting, June 22-23, 1944, Murray Bay, Que.

Society for the Promotion of Engineering Education. Annual meeting, June 22-25, 1944, Cincinnati, Ohio.

fabricating it have been decided upon the data necessary for determining the effect of welding procedure upon the ductility of the heated zone adjacent to the weld in plain carbon and low-alloy steels may be found in the guide. Apart from the data in the book only two tests are required—an end quench and a notch-bend of the steel. Part I of the guide explains the system, and part II is designed as an instruction manual in its use. The guide is intended to facilitate a prompt and thorough test of the proposed system by welding engineers. Development of the system was initiated by Lehigh University under the sponsorship of the Welding Research Council and later taken over by the National Defense Research Council. The Welding Research Council, 29 West 39th Street, New York 18, N. Y., is soliciting reports from industry on success or difficulty in the use of the system. Copies of the guide may be obtained for \$1.

Purdue Installs Power-Network Analyzer



D. D. Ewing (F '21) professor and head of the Purdue University school of electrical engineering, demonstrates the university's new network analyzer to representatives of the Midwest power companies which co-operated in its purchase and installation. Capable of solving in a few days, problems which would require months by the analytical method, the analyzer can reconstruct in miniature the operations of any power system. The available circuit elements can represent simultaneously 16 generator stations, 160 transmission lines and transformers, and 40 loads, which are adequate for studies on even the largest power systems. By setting up the projected system on the board, engineers planning additions of lines or equipment can judge the efficacy of the new equipment in advance. Particularly valuable are the possibilities of short-circuit studies for determining protective relaying settings. Such studies on an actual system would entail unwarranted damage. The co-operating companies to which the board will be available are: The American Gas and Electric Service Corporation, Cincinnati Gas and Electric Company, Dayton Power and Light Company, Indianapolis Power and Light Company, Louisville Gas and Electric Company, Northern Indiana Public Service Company, and the Public Service Company of Indiana. Other companies may obtain operating time upon application to the university. J. B. Ward (A '40) instructor in the school of engineering will direct operation of the board.

NEMA Adopts Induction- and Dielectric-Heating Standards

Seven new standards for electronic equipment for induction and dielectric heating have been adopted by the electronics section of the National Electrical Manufacturers Association. They are listed as follows:

- EL 5-5 Output Ratings
- EL 5-10 Ratings of Tubes and Parts
- EL 5-15 Radio Interference
- EL 5-20 Protection of Personnel
- EL 5-25 Protective Equipment
- EL 50-5 Induction Heating—Definition
- EL 50-10 Dielectric Heating—Definition

Copies of the standards may be obtained from NEMA headquarters 155 East 44th St., New York, N. Y.

JOINT ACTIVITIES

ASA Co-ordinates Symbols for Electrical Designs

A compilation of a consistent set of graphical symbols for electrical and electronic equipment, titled, "Co-ordination of Electrical Graphical Symbols," has been published as an American War Standard by the American Standards Association. In the War Standard all outright conflicts in usage have been eliminated. Alternate symbols

have been tolerated only where the use of a symbol is so deep-seated in an industry that change would cause undue hardship.

The problem of conflicting symbols had become acute particularly since the war when the divergent sets of symbols used by the power industry and the communications industry began to overlap because of the expansion of electronic devices in communication, control, and detecting devices. By compromise the new standard has obviated previous practice in which one symbol was sometimes used to indicate two different pieces of apparatus or two different symbols used for the same equipment. Representatives of technical societies, trade associations, the War and Navy Departments, the Aeronautical Board, the National Aircraft Standards Committee, and industrial organizations participated in developing the standard.

Copies of the new Standard Z32.11-1944 may be obtained for 10 cents a copy from the ASA, 29 West 39th Street, New York 18, N. Y.

Two Radio Standards

Issued by ASA

In an effort to increase production of radio parts the American Standards Association has completed two new American War Standards, "Power-Type Wire-Wound Rheostats" (C75.9-1944) and "Variable Wire-Wound Resistors" (C75.10-1944). It is expected that the Standards will be used in the design of new equipment; in preparation of new manufacturing facilities; and for procurement purposes.

Keyed to the requirements of the Armed Forces, both standards include applicable specifications and drawings; classification; materials and workmanship; general and detailed requirements; methods of sampling; inspection and tests; and packaging, packing, and marking for shipment. A combined committee of representatives of the radio industry and the Armed Forces drew up the standards, and they already have been adopted by the United States Navy Department's Bureau of Ships and the Signal Corps Standards Agency of the United States Army.

The main difference between the two Standards is the greater power dissipated by the power-type wound rheostat because of a higher operating temperature. The variable wire-wound resistor with its low operating temperature is employed chiefly in radio and electronic devices.

The Standard on the power-type rheostat is 50 cents per copy and the Standard on the variable resistor is 40 cents per copy. They may be obtained from the American Standards Association, 29 West 39th Street, New York 18, N. Y. They are available without charge for procurement purposes only from the Government agencies concerned.

ASA Approves Two Standards on Electrical Insulating Materials

Two standards of the American Society for Testing Materials have been approved recently by the American Standards Association. These are the previously approved and recently revised American Standard Tentative Methods of Testing Molded Materials

Used for Electrical Insulation (C59.1-1944) and the new American Standard Methods of Testing Sheet and Plate Materials Used in Electrical Insulation (C59.13-1943), developed by the ASTM committee on electrical insulating materials.

The first of these Standards applies to all solid electrical insulating materials (except dry-process porcelain) formed in molds by the application of pressure, either with or without heat, and includes only special instructions pertaining to the preparation and testing of these materials. Methods of test are described for acetone extraction, arc resistance, compressive strength, dielectric strength, deformation under load, distortion under heat, and similar conditions.

The second of these Standards covers the procedures for testing stiff, flat-sheet, and plate materials such as phenolic and other types of laminated sheets, hard rubber, asbestos, composition board, and others, to be used as electrical insulation, except as modified by the individual methods or specifications for a particular material. The standard includes definitions of terms used; directions for conditioning apparatus; and procedure for testing thickness, tensile strength, flexural strength, compressive strength, resistance to impact, water absorption, volatile matter, and the like.

Copies of the Standards are available and can be obtained from ASA, 29 West 39th St., New York, N. Y., at 25 cents per copy.

ECPD Issues Pamphlet on Joint Local Groups

A concise explanation of the plan recently devised by the Engineers' Council for Professional Development for the organization of joint local engineering groups to further the objectives of the Council on the level of the individual engineer is offered in a new eight-page pamphlet, "Will You Help?" Although the plan is directed primarily toward the local sections of the Council's eight participating societies other local engineering

organizations and interested groups are invited to take part. It is hoped that the pamphlet, which is available upon request, will stimulate growth of more groups such as have been organized to work in the local field for the establishment of engineering on a sound professional foundation. The four standing committees of ECPD are prepared to extend general guidance to the local groups. The committees also will assist the local organizers by answering questions, by supplying information about the other local groups, and by making suggestions based on their observations. Inquiries may be addressed to the Engineers' Council for Professional Development, 29 West 39th Street, New York 18, N. Y.

EDUCATION . . .

Rutgers University Organizes Research Council

Creation of a research council to promote research in all departments of the university has been announced by Rutgers University, New Brunswick, N. J.

A special fund has been placed at the disposal of the council and a survey of personnel and facilities is being made to determine the best projects for investment of new funds. Emphasis will be placed upon co-operative research between departments and between outside organizations and university departments. Applications for grants for next year are being considered now.

William H. Cole, professor of physiology and biochemistry, has been appointed director of the new council, and James L. Potter (A'41) professor of electrical engineering, has been named one of its nine members. Doctor Cole will represent the university in developing reciprocal arrangements with governmental, industrial, business, and professional institutions.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly under-

stood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Mercury Thermometers in 60-Cycle Fields

To the Editor:

There has been recurrent discussion concerning use of mercury thermometers in 60-cycle magnetic fields, because internal heating of the mercury by eddy currents tends to make the temperature indication higher than would be shown by a spirit thermometer in the same location. The amount of error is of interest because mercury instruments sometimes are preferable in other respects.

In testing a 2,666-kva 2,400-ampere reactor some years ago, mercury thermometers were observed to be registering several degrees higher than nearby spirit thermometers. Most of the difference may have been nonmagnetic in origin, however.

In a recent experiment by the writer, a difference of 0.6 degree centigrade was observed in a field of 40 kilolines per square inch. The setup comprised a water-cooled solenoid 4 inches in diameter and 4 inches long, with mercury and spirit thermometers corked into a small glass thermos flask, inside the winding. The mercury bulb was

$\frac{7}{32}$ inch in diameter by $\frac{3}{4}$ inch long. The test was run for 15 minutes, and the difference in readings became constant after ten minutes. Field strength was measured by a pickup coil wound on the outside of the flask; this coil also showed when the bulbs were centered in the maximum field. Since this field strength was much higher than would be encountered in almost any usual equipment, including reactors, it would appear that mercury thermometers of similar dimensions can be used freely in 60-cycle fields.

A moderate amount of searching has not brought to light any quantitative statements on this subject, and further information therefore would be much appreciated.

JEROME J. TAYLOR (A '40)

(Electrical engineer, Detroit (Mich.) Edison Company)

NEW BOOKS . . .

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Precision Measurement in the Metal Working Industry. Volume I, prepared by the Department of Education of International Business Machines Corporation. Syracuse University Press, Syracuse, N. Y., 1942. 263 pages, illustrated, 11 by 8 inches, cloth, \$2.75. (ESL.)

This is a revised edition of the manual on precision measurement and inspection methods in metal working originally prepared for use in training International Business Machines Corporation workers. Volume I contains the first seven chapters dealing with measurement in general, nonprecision line-gauged instruments, micrometer and vernier types, precision gauge blocks, fixed gauges, thread gauges, dial gauges, and test indicators. Volume II, now in process, will treat the more advanced types.

Rubber Red Book, Directory of the Rubber Industry. 1943 edition, fourth issue. Published biennially by *The Rubber Age*, New York 19, N. Y. 579 pages, illustrated, 9 $\frac{1}{2}$ by 6 inches, cloth, \$5. (ESL.)

This directory of the rubber industry lists the rubber manufacturers of the United States and Canada, the manufacturers of rubber machinery and accessories, and the suppliers of chemicals, fabrics, and crude rubber. The varieties of synthetic rubber and their makers are listed. Other listings include rubber reclaimers and scrap dealers, rubber derivatives and rubber latex, consultants, sales agents, technical journals, organizations, and a directory of men prominent in the industry.

Meteorology, Theoretical and Applied. By E. W. Hewson and R. W. Longley. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1944. 8 $\frac{1}{2}$ by 5 $\frac{1}{2}$ inches, cloth, \$4.75. (ESL.)

The object of this book is to give a well-rounded view of the essentials of meteorology. Part I deals with theoretical meteorology: the physical and thermodynamical characteristics of air; the movements of air masses; and the statistical analysis of meteorological data. Part II covers applied meteorology: instruments and observational procedures; climatology; map analysis and precasting procedure; and the applications of meteorology to other specialized fields.

Occupational Index, Volume 8, numbers 1-5, January, April, July, October, and Index, 1943. References 1-375. Occupational Index, Inc., New York University, New York, N. Y. 10 by 7 inches, paper, \$5, annual subscription. (ESL.)

This bibliography, issued quarterly, contains annotated references to current pamphlets, books, and magazine articles containing information about opportunities in various occupations. Over 300 publications are listed in 1943. The annotations are clear and informative. Indexes by author, title, and subject are provided. Both military and civilian occupations are covered.

Practical Design of Welded Steel Structures. By H. M. Priest. American Welding Society, 33 West 39th Street, New York 18, N. Y., 1943. 153 pages, illustrated, 8 by 5 inches, cloth, \$1. (ESL.)

The essentials of welding and welded construction are presented in concise form as a working manual for the practical welder and designer. The various welding processes, forms of joints, and weld testing are discussed. The general and detail design considerations for simple welded joints and connections precede their application to typical structural members. A separate chapter is devoted to the problem of fatigue.

Strength of Materials. By H. F. Girvin. International Textbook Company, Scranton, Pa., 1944. 357 pages, illustrated, 9 by 6 inches, cloth, \$3. (ESL.)

After a survey of the first courses in strength of materials given at our larger colleges, Professor Girvin prepared this textbook. It aims to give the student thorough training in basic principles and to avoid attention to specialized topics better treated in later courses in design. The area-moment method of determining deflections is emphasized. A large number of problems are included.

Materials Handbook. By G. S. Brady. Fifth edition. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1944. 765 pages, illustrated, 9 by 5 $\frac{3}{4}$ inches, cloth, \$5. (ESL.)

This handbook provides a quick source of information on the characteristics of materials of industrial importance. It will be useful to purchasing agents, designers, executives, and others. The arrangement is alphabetical with a good index to trade names and synonyms. The new edition has been revised carefully and is larger than preceding ones.

Modern Drafting. By W. H. Johnson and L. V. Newkirk. The Macmillan Company,

New York, N. Y., 1944. 197 pages, illustrated, 11 by 8 inches, cloth, \$2.50. (ESL.)

This textbook, intended for use by students at the high-school level, attempts to provide a course in the fundamentals of drafting and its industrial applications, which will enable the student to go to work. Chapters are devoted to pictorial drawing; sheet-metal, machine, and aircraft drafting; architectural drafting; and graphs and maps.

Power and Flight. By A. Jordanoff. Harper and Brothers, New York, N. Y., and London, England, 1944. 314 pages, illustrated, 10 by 7 inches, cloth, \$3.50. (ESL.)

A readable elementary text intended for students and mechanics on the aircraft power plant and its maintenance. It also will be useful to others who wish to know something about aircraft engines. The book is distinguished by over 400 illustrations which clarify the text.

PAMPHLETS . . .

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Valuations, Appraisals, Inventories. Ford, Bacon and Davis, Inc., 39 Broadway, New York, N. Y., 11 pages.

Hearings Before the Subcommittee on Military Affairs, United States Senate, on Problems of War Contracts and Their Relations to Small Business. Smaller War Plants Corporation, Washington, D. C., 27 pages.

War Production Issue, May Facts. George S. May Company, 2600 North Shore Avenue, Chicago, Ill., 8 pages.

Resistance Welding. R. T. Gillette, General Electric Company, Schenectady, N. Y., 28 pages.

Fourteenth Report to Congress on Lend-Lease Operations. Superintendent of Documents, United States Government Printing Office, Washington 25, D. C., 84 pages, 20 cents.

Scheduling Primer. War Production Board, Washington, D. C., 16 pages.

A Table of Common Hazardous Chemicals. National Fire Protection Association, 60 Batterymarch Street, Boston 10, Mass., 31 pages, 30 cents.

Radio Markets After the War. Institute of Radio Engineers, Inc., 330 West 42d Street, New York 18, N. Y., 26 pages, 50 cents.

Distribution of Safety Equipment by Major Consuming Industries—1943. War Production Board, Washington, D. C., unpag.

American Standard Symbols for Electrical Diagrams. I-T-E Circuit Breaker Company, 19th and Hamilton Streets, Philadelphia 30, Pa., chart.

UL Symbol of Safety. Underwriters' Laboratories, Inc., 207 East Ohio Street, Chicago, Ill., 32 pages.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume
Any discussion of these papers will appear in the June 1944 Supplement to Electrical Engineering—Transactions Section

Study of Artificial Respiration on Anesthetized Men

W. B. KOUWENHOVEN
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IN an earlier paper¹ the authors reported the results of a study of the methods of artificial respiration when conscious subjects were used. In that study three methods of artificial respiration were investigated: namely, the Schafer prone-pressure method, the modified prone-pressure method, in which the hands were rolled or snapped off the subject's back, and the pole-top method.² A total of 15 men was tested, and the volume of air moved by the three methods of artificial respiration was measured. All of these men were conscious, and the results indicated that all the methods were adequate, with the pole-top method in the lead. Although all of the subjects were intelligent and presumably capable of completely relaxed passivity, such results are always open to the criticism that the subject may have co-operated, perhaps unintentionally.

The investigation was, therefore, repeated, using anesthetized subjects in whom there is no possibility of co-operative aid. One of the barbiturates, sodium pentothal, was administered intravenously. This drug promptly effects unconsciousness and complete muscular relaxation. At the outset it depresses the respiration, which quickly assumes a comparatively steady state. This can be maintained safely for a considerable period of time by the judicious administration of repetitive doses of the drug. Subjects A, B, and C were studied and

were carried through the procedure successfully.

Experimental Procedure

The subject's breathing was first measured while he was in a conscious state. A mask was placed firmly over his nose and mouth and connected to a spirometer (gas meter) which measured the volume of air breathed. A pneumograph was placed around the chest to ascertain the amount of chest expansion and contraction. A revolving smoked drum recorded the amount of air passing through the gas meter, the chest movement, and the time. The data thus secured served to determine the amount of air breathed in the unit of time necessary to complete the experiment.

The subject then placed himself in a prone position on a mat lying on the floor. After five minutes had been allowed for him to relax, a record of his natural breathing was taken. A trained operator then gave him artificial respiration, employing the standard Schafer method, and then after a suitable interval, the modified Schafer method. The conscious subject, with the mask still in place, climbed a pole that was mounted in a laboratory, and seated himself astride the safety strap of the operator. His position on the pole was similar to that of a lineman who had received a shock, except that his feet were only about one foot above the floor. The subject's natural breathing was recorded, and then the operator applied the pole-top method of artificial respiration.

The anesthetic was then administered to the subject while he was still on the pole and astride the operator's safety strap.

The subject became unconscious quickly, and, after the elapse of a few minutes, his breathing reached a steady state. This was recorded. Then artificial respiration was administered by the operator, using the pole-top method.

When this was completed, the subject was lifted down from the pole, while still in an unconscious state, and placed in a prone position on the mat. The gas mask was not disturbed in this operation. The subject's natural breathing in this prone position and unconscious state was recorded. Then the operator applied artificial respiration by the standard and modified methods in turn. When the experiment had been completed, the administration of the anesthetic was stopped, and the gas mask and pneumograph were removed. The subject was made comfortable and allowed to rest until he was fully conscious. None of the subjects experienced ill effects from the procedure.

Pauses of several minutes were interspersed between each operation in order that the subject's respiration might become normal under the existing conditions before the next step of the experimental procedure. The results obtained in an experiment of this character are not strictly comparable to what might be expected in individuals in which all respiratory activity has ceased, but they probably are as close as laboratory conditions can provide.

The data taken are presented in Table I. It will be noted that the imposed respiratory rate during artificial respiration is less than in natural breathing. This is particularly true of the subjects when they are in an unconscious condition. The amount of air moved per respiration is, however, considerably greater. It is thus evident that all three methods of artificial respiration are more than adequate to supply the necessary ventilation of the lungs. In the last column of Table I the average results reported on the 15 conscious subjects in the earlier paper¹ are given for the purpose of comparison.

In Table II the data are expressed as

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Table I

Conditions	A	B	C	Average A, B, C	Average 15 Subjects
	22 Years 139 Pounds	38 Years 160 Pounds	38 Years 167 Pounds		
Conscious					
Natural breathing in prone position					
Respirations per minute.....	15.....	14.....	11.....	13.....	13
Cubic centimeters per respiration.....	375.....	625.....	770.....	590.....	545
Cubic centimeters per minute.....				7,670.....	7,090
Original Schafer artificial respiration*					
Respirations per minute.....	14.....	10.....	12.....	12.....	11
Cubic centimeters per respiration.....	424.....	1,000.....	1,111.....	845.....	868
Cubic centimeters per minute.....				10,150.....	9,540
Modified Schafer artificial respiration**					
Respirations per minute.....	13.....	11.....	10.....	11.....	11
Cubic centimeters per respiration.....	457.....	1,250.....	1,250.....	986.....	1,028
Cubic centimeters per minute.....				10,850.....	10,300
Natural breathing in trunk-vertical position					
Respirations per minute.....	14.....	16.....	10.....	13.....	15
Cubic centimeters per respiration.....	413.....	625.....	1,000.....	679.....	558
Cubic centimeters per minute.....				8,830.....	8,370
Pole-top artificial respiration					
Respirations per minute.....	10.....	14.....	10.....	11.....	10
Cubic centimeters per respiration.....	875.....	1,111.....	1,111.....	1,032.....	1,363
Cubic centimeters per minute.....				11,340.....	13,630
Unconscious					
Natural breathing in prone position					
Respirations per minute.....	17.....	18.....	19.....	18.....	18
Cubic centimeters per respiration.....	172.....	384.....	237.....	264.....	264
Cubic centimeters per minute.....				4,752.....	
Original Schafer artificial respiration*					
Respiration per minute.....	11.....	11.....	12.....	11.....	11
Cubic centimeters per respiration.....	430.....	714.....	625.....	590.....	590
Cubic centimeters per minute.....				6,490.....	
Modified Schafer artificial respiration**					
Respirations per minute.....	9.5.....	10.....	12.....	10.....	10
Cubic centimeters per respiration.....	571.....	910.....	768.....	746.....	746
Cubic centimeters per minute.....				7,460.....	
Natural breathing in trunk-vertical position					
Respirations per minute.....	21.....	17.....	19.....	19.....	19
Cubic centimeters per respiration.....	170.....	367.....	280.....	272.....	272
Cubic centimeters per minute.....				5,168.....	
Pole-top artificial respiration					
Respirations per minute.....	11.....	12.....	13.....	12.....	12
Cubic centimeters per respiration.....	714.....	912.....	770.....	799.....	799
Cubic centimeters per minute.....				9,588.....	

* Hands held in position between pressure strokes.

** Hands allowed to slip off at the end of each pressure stroke.

Table II

	Percentage Increase Over Control Period— Air Moved Per Minute		Percentage Increase Over Control Period— Air Moved Per Respiration		Percentage Difference in Air Moved Per Minute by Artificial Respiration While Patient Is Anesthe- tized Compared With Normal Breathing While Patient Is Conscious
	Conscious	Anesthe- tized	Conscious	Anesthe- tized	
Original Schafer artificial respiration.....	32 (33) *	37.....	43 (59) *	123.....	15 per cent decrease
Modified Schafer artificial respiration.....	41 (60) *	57.....	67 (89) *	183.....	3 per cent decrease
Pole-top artificial method ..	29 (63) *	86.....	52 (144) *	194.....	9 per cent increase

* Percentages for 15 conscious subjects, see reference 1.

percentage increases or decreases of the amount of air moved per respiration and per minute over the corresponding periods of natural conscious breathing of the three subjects. It is evident that the air moved per respiration under artificial respiration is equal to, or greater than, the natural breathing of the conscious

subjects. The number of respirations per minute is less for the artificial respiration than for the natural breathing of the conscious subjects. In the cases of both Schafer methods there is a decrease in the air moved per minute in the unconscious state as compared with the normal breathing. The pole-top method records

a slight increase in the volume of air moved per minute. Had the tempo of artificial respiration been increased to 13 times per minute, all three methods would have given equal or greater volume of air breathed per minute than for natural conscious breathing.

The bracketed figures in Table II are taken from the earlier paper.¹ They show a higher percentage increase in the volume of air moved than was found for the three subjects reported here. This suggests that a psychological factor may be involved in working with conscious subjects. The results obtained with the unconscious subjects are, however, not subject to this factor.

Conclusions

These studies give evidence of the relative efficiency of the three methods of artificial respiration studied, and so far as we know they represent the first effort to evaluate the worth of artificial respiration³ in subjects under general anesthesia.

The data presented indicate that an equal or greater amount of air is moved in the unconscious (anesthetized) than in the conscious subject with each respiratory act. The modified Schafer method (hands allowed to slip off at the end of every stroke) is superior to the standard Schafer method, and the pole-top method is more efficacious in the trunk vertical position than the Schafer methods in the prone position.

It is apparent that all three methods of artificial respiration studied are more than adequate to supply the requisite pulmonary ventilation.

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Aircraft Signal Systems

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Synopsis: Because the selection of aircraft warning devices has not, in most signal installations, provided the pilot with dependable warnings of dangerous conditions, this paper proposes that aircraft signal devices should be designed and installed in compliance with the pilot's requirements as expressed in three design principles.

The publication describes the weaknesses of current signal devices; it recommends signal light indicators that are bright enough to be seen under direct sunlight; and it illustrates and describes an automatic dimming control that operates as a function of natural light, independent of pilot actions.

FORGETFULNESS on the part of the pilot to extend retractable-type landing gears initiated the requirements for positive-warning signal systems on airplanes. Malfunctioning of important equipment and co-ordination of crew activities brought about the requirements for informative signals in aircraft.

In addition to these requirements, pilots demanded warning signals for such items as gears "not locked," flaps "not down," fuel pressure "low," fuel level "low," oil pressure "low," and cabin "pressurization" "off." Informative signals were demanded for oxygen pressure "low," warning of icing conditions, bombing signals, paratroop "jump" signals, passenger call signals, crew call signals, and so forth.

To provide these signals for the pilot's use, it is necessary that the signal indicators should be designed correctly and that airplanes should be equipped with the necessary mechanical or electric pickups, consisting of easily serviceable actuating devices or limit switches, pressure switches, temperature switches, and control relays. These electric-signal pickup devices and controls have been available for some time as serviceable and reliable parts and are beyond the scope of this paper.

The signal indicator is the only controversial item in the airplane signal system, and manufacturers, in attempting to provide suitable signal indicators, have re-

sorted to mechanical flags, vibrators, bells, horns, position indicators, indicator lights, telltale panels, and similar devices to serve as warning signals and as informative signals. The selection of these devices for the signal indications on airplanes has been made, in too many cases, by compromise decisions which have been influenced by restrictions rather than by principles. The result of such selection of indicators is that many signal systems on airplanes are not serving the purpose intended.

The purpose of this paper, therefore, is to outline the design principles that aircraft signal indicators should satisfy, to discuss existing signal indicative devices and to what extent they comply with these principles, and to suggest signal-system methods for improving the pilot's "workshop" so as to relieve him of unnecessary duties and thereby lessen pilot fatigue.

Design Principles

The following principles usually are common to the design of all warning signal indicators and to the design of most of the informative signal indicators in aircraft signal systems.

SIGNALS MUST BE ABSOLUTE

The first principle to be satisfied in providing signal indications is that the signal device should, by independent action, bring about decisive, positive, and effective action. Thus, aircraft-warning signal devices should, in themselves, provide indications which incite the pilot's reflexes in such a manner that he will change quickly and unquestionably to the obvious alternate course of action. Informative signal devices complying with this principle should show, in addition, directive indications. This directive-type indication is necessary to avoid creating any degree of confusion in the mind of the pilot or crew member, as the course of action may be perplexing for the moment.

SIGNALS DISTINCT

The second basic rule to be followed in designing a signal indicator is to construct the indicative device so that it will emit signals which are distinct, abrupt, attractive, inescapable, and in definite contrast

to everything in the proximity of the signal during any flight condition.

SIGNALS NOT A HAZARD

The third principle to be observed in designing signal indications is to be sure that the signal does not constitute a hazard and thereby handicap the pilot in performing his operations. Violation of this principle is exemplified in installations where the brilliance of light signals is not modulated as a function of the natural light.

These principles are not new, and they are seldom ignored by the commercial control engineer. Most aircraft engineers would like to follow these laws but cannot because of the inertia of the aircraft industry against cost of the correct device in terms of weight, special design studies, and manufacturing or procurement complications. It is because of this cumbersome inertia and a desire for improvement of aircraft signal systems that the comparative description of signal devices is discussed in detail in the next section of this paper.

Existing Systems

VISUAL MECHANICAL SIGNALS

Flags and mechanical indicators are the oldest type of warning and informative signal devices. They have been used in the airplane industry on small airplanes for such items as landing gear, flap, and tab position indicators. Examples of this type include push-rod and vane indicators on landing-gear mechanisms, spring- or cable-actuated scale and pointer combinations, solenoid-operated flags, and solenoid-operated targets that become visible by natural light or black light.

These devices have been selected by airplane manufacturers, because they are simple to design, install, and maintain, and because of the small number of parts that need to be replaced.

Fundamentally, all of these visual-type indicators depend on their warning by reflected light. The dependence on auxiliary light sources, and the fact that the signals are not abrupt or distinct enough to attract consistently the pilot's attention cause these signals to be considered undesirable warning signals.

In general, it may be stated that flags, mechanical indicators, and solenoid-actuated indicators obviously comply with the third principle, but do not satisfy completely the first and second principles discussed in the preceding section. These devices do not satisfy the first principle,

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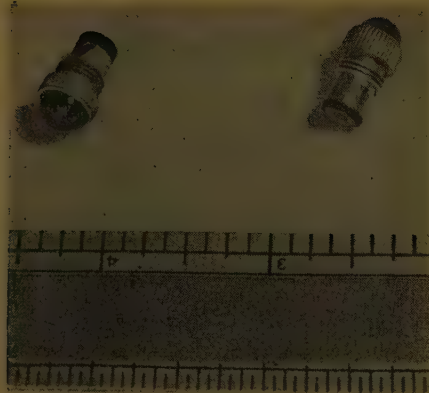


Figure 1. Lens-end signal lamps. General Electric Company T 1¹/₄, 3 volts, 3 amperes, BM base

because they are not self-sufficient in themselves, for the reasons that they require auxiliary illumination, are not always positive, and, therefore, do not bring about immediate action. This type of signal does not comply with the second principle, because its indications are not abrupt enough, are not inescapable from the pilot's vision, and are not in sharp contrast to all other images meeting the eye.

VIBRATORS

Foot-pedal vibrator-type signals partly comply with all three design principles, but in most installations signals of this type do not fulfill the requirements of the first and second principles. Many pilots have expressed difficulty in interpreting the meaning of the signal, while others complained of the lack of contrast of the vibration signal with the normal vibration of the airplane.

AUDIBLE SIGNALS

On practically all large airplanes designers have installed audible-type signals such as high-frequency vibrators, bells, and horns as warning and informative

signal devices. Although these audible signals, when properly installed, comply with all three of the design principles, the characteristics of this type of signal limits the installation to one or two signals (the distance warning signals can be installed from the pilot's ear) and to the objections raised by air-line operators if warning or informative call signals can be heard by the passengers.

The advantages claimed for this type signal include:

1. The convenience of mounting in waste spaces.
2. The fact that no modulation of the signal volume is required during flight operations.
3. The fact that the need of replacements is rare.
4. Convenience of electric wiring for remote actuation of the audible indicator.

An example of audible warning or informative-signal indicator is the vibrator-type horn built to conform to Army-Navy specification AN-S-8.

Figure 3. Telltale device as installed in Curtiss-Wright AT-9 airplanes

This telltale is a visual warning device mounted on the instrument panel and contains 18 warning and informative signals as shown. Constant checking and rechecking of the instruments by the pilots has been eliminated, as this device is electrically connected to necessary instruments, controls, and component operating parts of the airplane, in such manner as to report immediately and constantly on their operation. These operations are shown by individual lighted signals on the telltale panel which are operated by limit switches, pressure switches, and so forth. The signals, as arranged, function as a "negative-warning" signal device, as a perfectly dark panel indicates correct operation of the items

INSTRUMENT-TYPE SIGNAL INDICATIONS

Position indicators in some cases have been used to provide warning or danger signals as well as informative signals. Many aircraft manufacturers have installed indicators of this type for the purpose of combining warning or danger signals with informative position indications in a centralized location.

These combination position and warning-signal indicators are available with two types of warning signals. In one type the warning signals are manifest by mechanical flags which disappear when the landing-gear units are in the locked position. The other type indicator utilizes signal lamps as warning signals.

This combination instrument, known as GE 8DJ4Y6, when equipped with the signal lights, is an excellent centralized signal and position device in that it satisfies all three of the design principles, provided that the brilliance of the light matches the natural light. As will be discussed under light signals, the brilliancy of the signal lights should be controlled by an automatic modulating or automatic step-type control to maintain proper brilliancy of the signal lamp to satisfy night and day flight conditions.

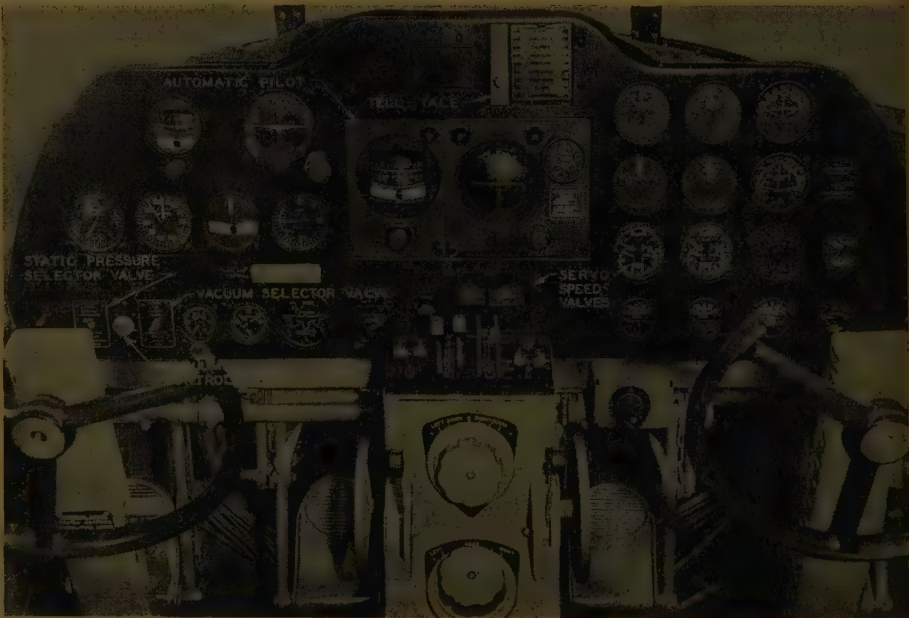
LIGHT SIGNALS

Colored lights have been used very effectively as warning and informative signals on all types of airplanes. The installation of these lights as warning signals has been accomplished in the conventional industrial manner, that is, a colored lens shielding a clear electric lamp.

The greatest disadvantage of light signals in any signal system is the necessity for controlling the brilliancy of the



Figure 2. Photoelectric dimming control



signal light as a function of the natural light. It is this disadvantage that causes the criticism of light signals. This criticism is, of course, warranted, as light signals that are too dim to be distinct in bright sunlight do not comply with the second design principle, whereas light signals that are too bright at night constitute a hazard to the pilot.

In view of this brightness factor, most airplane manufacturers have provided manually operated mechanical or electrical dimming devices to adjust the brilliance of the light signal to correspond to the natural light in the cockpit or control room. These manual devices, however, do not solve the light-intensity control problem for the reason that the pilot or crew member is not reminded to turn up the intensity of the signal light to match the sunlight conditions. Thus, it often happens during daylight operation that the warning light is energized, but no signal warning is noticed by the pilot for the reason that the light had been dimmed previously for night intensity. Even with semiautomatic schemes this condition still exists. For example, in signal-light installations where dimming is accomplished by the introduction of resistors by relay in the signal-light circuit by turning the navigation lights "on," the failure to increase the signal intensity is not prevented. Only the possibilities are re-
sponding illuminated-directive nomenclature all arranged on a panel 3 by 3 1/2 inches.

This device, in addition to showing warning and informative signals, includes directive signals to indicate to the pilot incorrect setting of important controls such as propeller, mixture, manifold pressure, carburetor heat, and trim tabs. Actuation of these directive signals in the telltale panel is accomplished by automatic switching that is a combined function of the control setting and the flight regime.

Considered as a whole, this device complies with all three signal-indication design principles, except those conditions under which the second principle is violated. Like the manual-control shutter-dimmed signal lamps previously mentioned, the telltale unit is susceptible to daytime operating conditions where the dimming shield could be partially closed for night operations, and the pilot would overlook the telltale signals. As was discussed under "Light Signals," an automatic dimming device would correct this difficulty, and the telltale signal indicator would then satisfy all three design principles.

Concluding Recommendations

From the discussion given in this paper, it is recommended that all warning and informative signals should be light signals which are bright enough to be seen under direct sunlight. As part of this recommendation, it is suggested that the light intensity of the warning and informative signals should be controlled automatically as a function of day or night operation. For special requirements the light intensity should be modulated automatically or adjusted in steps to correspond with the natural light. Referring to the three design principles mentioned at the beginning of this paper, it is believed that a signal indicator complying with these suggestions will provide light signals which are absolute, always can be detected, and will not constitute a hazard to the pilot.

It is further suggested that to reduce pilot fatigue and to eliminate unnecessary searching of instrument indications more signals should be added to the airplane signal system. By the same reasoning it is recommended that these additional signals should be grouped into a centralized location in a manner similar to that utilized by the telltale panel shown in Figure 3.

able for aircraft uses, with which off and on can be distinguished readily under the direct rays of the sun.

This lamp was designed especially for low-voltage operation to insure long life (at least 250 hours) and to use a heavier and less-destructible filament. The lens in the lamp end is similar to the lens used in a "penlite"-type flash-light lamp. The lamps have been supplied in red, amber, blue, clear, and green.

PHOTOELECTRONIC DIMMING DEVICE

The photoelectronic dimming-control device shown in Figure 2 is referred to as General Electric 7505-L-108. This automatic-control unit can be obtained to actuate automatically a relay, to open or close resistor circuits, which dims or brightens any number of signal lamps in accordance with the requirements for twilight or daylight.

As the photoelectronic tube is sensitive to any degree of light changes from one-foot candle and upward, the selection of photoelectronic units for any particular airplane can be obtained for dimming control in as many steps as desired.

The photoelectronic device shown in Figure 2 consists of a photoelectric tube, amplifier tube, sensitive relay, resistor, and mounting. The unit, as pictured, weighs less than a pound and operates from any 24-volt d-c supply.

ELECTRIC CIGARETTE-LIGHTER-TYPE DIMMING CONTROL

Another automatic device has been designed to control the dimming of signal lights, but the weight is about the same, and it does not offer complete control. This proposed device is a thermal time-delay switch which instantly dims the signal light for a five-minute period only, then snaps to the original bright position in much the same manner as an electric cigarette lighter. This device does not permit the signal-system installation to satisfy completely the third design principle, as it repeatedly constitutes a momentary hazard during night-flight operations.

TELLTALE

The telltale device shown in Figure 3, manufactured by the American Automatic Company GH-70,350, is a centralized signal indicator which incorporates all of the control-room signals into one compact panel. Installation, as made on many hundreds of airplanes, provides for 18 light-signal indications with the cor-

BRIGHT-BEAM LIGHT AND PHOTOELECTRONIC DIMMING DEVICE

This year a signal-light system has been perfected that will satisfy all three design principles. Figure 1 shows the signal light itself, and Figure 2 illustrates the photoelectronic dimming device which controls the brilliance of any number of signal lights as a function of the natural light without any attention on the part of the pilot or crew member.

NEW SIGNAL LAMP

The lamp shown in Figure 1, although similar to the General Electric Mazda 319 or 320 28-volt bombing signal lamp, is identified as a General Electric $T 1\frac{1}{4}$, three-volt 0.30-ampere lens-end BM-type-base signal lamp.* This lamp was developed to produce a high-candle-power light beam which would serve as a distinct and inescapable light signal in direct sunlight. As of this writing, this lamp is the only unshielded signal lamp, suit-

* BM-type base refers to the special lamp base designed to match the Bardwell-McAlister lamp socket.

Cultural Training of the Engineer

A. BOYAJIAN
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It is generally recognized that a professional man must have a certain amount of cultural training, in addition to the technical, so as to be better balanced, more useful to the society, and more successful; and engineering curricula generally make provision for it. However, it appears questionable whether the cultural program is as well suited to its objectives as the technical programs are to theirs. As a parent, the author had occasion to look into this matter during the past several years and was led to the conclusion that the quality of the conception and execution of the cultural training of the engineer is definitely inferior to that of his technical training.

Although the author would be pleased if this paper should stimulate a general discussion and careful review of the situation by competent authorities, leading to its amelioration, yet his immediate purpose is more modest—to share some of his thoughts on this matter with the parents of prospective technical students.*

A Basis for Planning

Considering the great variety of cultural subjects and the wide divergence of tastes, it may be a question whether a generally acceptable cultural program can be planned. Think of the cultural value and fascination of the fine arts—music, painting, sculpture, architecture, dramatics, dancing, and so forth. Of the classics—poetry, fiction, drama, essay, mythology, and so forth. Of philosophy—logic, metaphysics, and so forth. Of the social subjects—sociology, anthropology, even archeology, politics, economics, and so forth. And history—political, social, revolutionary, and so forth. And—but why enumerate more?

What shall we recommend to our sons specializing in science or technology? Is there a basis for choice other than individual taste?

I think there is such a basis, and it is to be found in certain common and urgent needs of the average student. The short-

age of available time for this purpose makes it imperative to pass by most of the fascinating subjects mentioned, to assure that certain "must" subjects are properly taken care of first.

Student's Needs

I think we can get general agreement on at least the following three cultural needs of the average student as fundamental:

1. Knowledge of and skill in studying efficiently.
2. Knowledge of and skill in dealing with himself and others successfully.
3. Ability to express himself well in speech and writing.

Let us examine each item in its turn.

1. How to study is perhaps the most pressing problem of the freshman. Little or no instruction is given in this matter by the faculty; in its place, frequent quizzes are given to "put the screws on" the freshman. He must discover for himself how to study or be eliminated. This should have been learned at the high school, but it was not. The fellow was then still a "darling boy," and we regretted that he had to do homework at all, instead of being out in the fresh air or in bed, or having fun with other young people—boys and girls. Unprepared for serious study, the freshmen fret and swear, smoke and scribble and spit, and, finally, about half of them evolve some temporary *modus vivendi* whereby they survive for four years to receive their diplomas. After that, books and studies may go overboard. Four years of those things were too much already!

2. How to deal with himself and others is another great problem of the student, but he is not generally aware of it, and no particular attention is paid to it by the faculty.

Years ago, at a gathering of young engineers, a big engineering executive was asked for the key to success. "Boys," he said, "Pay close attention to your mathematics;" but, later, when the same question was put to him again, now by a friend of his and in the privacy of his home library, the answer was: "George, the key to success in engineering is 40 per cent technology, 60 per cent diplomacy."

Whether it is called diplomacy, or social psychology, or simply human relations, a certain amount of proficiency in it is essential in the successful practice of engineering. More of it is required, of course, in managerial positions than in the ranks, but that the latter group frequently do not possess even the modicum that they need is indicated by the published experience of one large organization to the effect that in a period of depression the selection of technical men for layoff was more often for lack of co-operativeness than for lack of technical ability.¹

It is probably safe to predict that the student who is brilliant in technology but just passable in human relations will in time work for the one who was just passable in technology but brilliant in human relations.

3. As for self-expression, technical schools pay only a limited attention to speech but are generally interested in writing, and in this the freshman is traditionally deficient. This deficiency is supposed to be due to lack of knowledge of the English language, and so the freshman is required to take English. But the principles of good writing are the same in any language, so good writing cannot be a matter of knowing the English language. Good writing can be done (frequently is done by the masters) in various dialects and slang; it can be done in basic English, even in pigeon English! Think of the gems in negro dialect! Knowledge of good English usage is of course highly desirable, but too much is expected of it when it is assumed that knowledge of English is the main thing in writing well.

Just because writing is important, speaking should not be treated casually. Speaking ability is a greater asset for an executive than writing ability. After all, should the necessity arise, it is possible to hire someone to write for you but not to speak for you. Furthermore, a good speaker can always produce a good manuscript by dictating as if he were giving a talk; but let a person talk as if he were writing a technical paper—what a disappointment that would be! Dr. Heiser has told us the secret of how he wrote his best seller, "An American Doctor's Odyssey." He realized that if he sat down to write his experiences, the product would probably be "a dry Rockefeller Foundation report." So he changed his plan. He knew that through years of practice he could talk fairly interestingly, so he hired an alert newspaperman to interview him, and a stenographer to record the interview. A best seller was

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* The views expressed here are those of the author himself and do not necessarily represent those of the company with which he is associated.

thus produced in a short time and without the usual drudgery of book writing.

I believe that for the average professional man the ability to speak before a group clearly, convincingly, and gracefully is a greater asset than ability to write well.

Urgency of the Problem

These three needs of the student cannot be postponed. He must acquire in his freshman year not only an efficient study technique, but also a variety of other habits essential to a successful personality. The college term, particularly the freshman year, is the terminal period of transition from the plastic to the relatively nonplastic phase of life and may be looked upon as the student's last opportunity to shape his personality into a desirable pattern. Soon he will be "set"; he will become a mere "walking bundle of habits," to quote William James, the psychologist. A complex network of intellectual, emotional, and motor habits will then constitute his entire personality and will determine even the details of his professional style and judgment. If this complex of habits is developed haphazardly and unawares, what probability would there be of anything but a mediocre personality developing, unless an exceptional heredity or a great inspiration or an exceptional set of circumstances should exist?

Credit units in classics and metaphysical speculation may be helpful but would not assure the kind of culture that a parent is likely to contemplate for his son. Furthermore, culture has not been acquired until it has become second nature through habit. The college years therefore should be utilized eagerly as the student's last opportunity to form these habits by practice with reasonable ease and under competent guidance.

Meeting the Needs

The basic cultural course generally required at the present time is English, but it is the opinion of this writer that if the foregoing needs of the student are true, they can be met best by practical psychology. It is not advocated that English be dropped but rather that it be approached as a problem in psychology rather than one in language.

Of course, a course in psychology is not necessarily cultural. It will not be so unless it is competently planned and conducted for this end. Let us note some of the features of such a course.

(a). The most important topic in

practical psychology for our purpose is that of habit. The classic Chapter III on habit in James's two-volume psychology (or its equivalent) should be used as the text for half a dozen lessons, coupled with a judiciously chosen set of exercises in habit formation. The student should realize that there is infinitely more to habit than nail-biting or smoking; that it is the one great principle of personal efficiency, because it is the principle of mechanization—automatization—of human behavior; and that not the breaking of so-called bad habits but the building up of his idealized social and professional personality through conscious, systematic, and habitual formation of habits is the major interest of habit psychology. As the student is made habit-conscious and as he develops a few judiciously chosen pleasant and profitable habits as laboratory exercises and gets the "feel" of it, he will be incidentally forming the most important habit—the master habit—namely, the habit of soundly planning and promptly mechanizing as much of his routine life as possible so that his mind may be relieved of routine drudgery and be set free to engage itself in more pleasant tasks and greater achievements. With proper work, study, play, and social habits formed (or at least well started) in the freshman year, the student is prepared for the most efficient utilization of his time and abilities for the development of his professional skills and personality during the following three years.

Habit psychology is a basic principle of any training, for training is primarily the conversion of knowledge into habit patterns by practice. If one thinks that the development of skill, rather than that of habit patterns, is the primary feature of training, he may do well to consult a good reference on habit psychology, in which he will discover that habit formation is the foundation of development of skills; for, after all, the major instrumentality in the development of skills is practice, and practice is inseparable from habit formation.

Many psychologists, engrossed in their specialties, do not seem to be actively aware of these things. The eminent psychologist, Dr. Link, has confessed as much—that he was not alive to these things until he observed the needs of his adolescent children.²¹³

(b). The next most important topic in practical psychology is human motivation. Properly taught, this should enable the student to see quickly the other fellow's point of view which generally amounts to his motivation. Much of our nontechnical reasoning, especially in

arguments, is nothing but rationalization, defense, and wishful thinking; in other words, biased or emotional thinking. That is why arguers never get anywhere with proofs. That is why an appropriate incentive convinces people so much better than logical evidence; and, as Hitler has demonstrated it, if the incentive is there, people will easily believe the biggest lies. "The will to believe . . ."

(c). The thought process and principles of clear thinking are naturally another important topic in psychology to be made clear to the freshman. Advertising psychology, political publicity, propaganda analysis, and scientific thinking, may be treated here in condensed form with great benefit and interest to the student.

(d). Then the eyes of the student must be opened to the power of attention and its significance towards his academic success. He should be enabled to see that the marvels of hypnotism are merely the product of an undistracted and concentrated attention; and that, if he wishes to be able to match the apparently superior power, intelligence, and memory of a hypnotized person, without the hocus-pocus of hypnotism, he can do so by cultivating his power of concentration. Would he then have any difficulty in studying at college or concentrating on creative work later?

(e). Practical psychology naturally forms the foundation of successful public speaking also. Many teachers of public speaking preoccupy the class with voice, posture, and other details to the exclusion of a psychological analysis of why a given speech is good or bad. "Not what to say but how to say it" is the watchword of some of them, the "how" being interpreted rather narrowly. But "what to say" is incomparably more important than "how to say it." If the presentations of papers at the AIEE meetings are frequently unsatisfactory, the basic reason, I think, is a lack of understanding of the psychology of the audience. The speaker probably is talking to a few specialists like himself sitting near the front to hear him well. That is why the rest don't hear him well; and when they do hear him, they do not understand what he is saying. I expect that if the psychology of the speaker is corrected, his voice and other important faults will automatically correct themselves.

Out of the mass of thoughts that are always available within the scope of the subject and the knowledge of the speaker, the selection of those which are best adapted to the background of the audience, the arrangement of those thoughts

in a logical sequence, the phrasing of them in graceful fashion, and their presentation in an audible pleasing manner, is the common sense of good speaking as the audience itself would define it; and the audience, as the customer, is right.

It is well enough to have public speaking taught to technical students by professional public-speaking teachers, but in some cases it may be necessary to supplement such instruction by having one or more technical men gifted in public speaking and able to make psychological analysis of a given speech sit in at the classes as audience and critics.

(f). The basis of good technical writing also has to be practical—common sense—psychology. This requires the selection of essential information, its arrangement in logical order, and its expression in a manner that will be clear and interesting to the intended readers. How little the study of the English language has to do with this! The knowledge of English—vocabulary and grammar—of the average freshman is fully adequate for his needs. The training he needs is in organizing his thoughts and expressing them in the words he knows. Of course, the study of the masters of English style is helpful and to be recommended within the very limited time available for that particular purpose, but we must not also forget the desirability of developing the student's own individual style. Too much emphasis on masters can destroy the student's individual style.

The merits of the student's English composition or technical report should be analyzed and appraised not from the standpoint of language but from the standpoint of the psychological principles of holding the reader's attention, imparting information to him and influencing his reaction in a desired direction. A course in English composition in which the instructor does no more than editorial corrections, I should consider a waste of student's time.

(g). The success of a course in English literature as a cultural medium depends on how it is selected and how approached. The point of view of a professional "litterateur" can have little cultural value for the engineer. For instance, I pick up a book by an eminent literary critic, entitled something like "The Stories I Have Enjoyed." I read a selection and am disgusted—no big idea, no real human interest in it. Then I find out that the critic selected it because the technique of that kind of a story is considered very difficult, and the author of this story "got away with it." Over and over again I have observed literary critics (and musical

critics) discuss at length considerations that can be of very little interest to those with only a general cultural interest in the matter.

What makes great literature great—the kind that lives through the centuries—is not its linguistic skill, but the profound insight into human nature that it exhibits; for instance, Shakespeare. But even the cultural value of a course in Shakespeare can be spoiled for the engineer by approaching it from the standpoint of literary technique.

In order to serve best the interests of the engineer, the teacher of literature must bear in mind constantly that what is needed is primarily a literature-appreciation course, carrying with it the following corollaries:

1. The teacher will have to work harder than the students. Especially in the composition work, he should be able and willing to rewrite the student's material and explain to him why one was bad and the other one is good.
2. Selections for reading must be chosen carefully and abridged to the limit to save the student's time. It will be better to err on the side of making it a "snap" course, rather than a difficult course which will antagonize the student and make him hate literature ever after. I should consider it a highly successful course if in literature the teacher accomplished no more than infusing the student with such an appreciation of good literature that the student will continue reading it in later years.
3. Engineering students should not be combined with those majoring in literature and made to follow the latter's volume of work and point of view.

Broader Obligations

The engineer is frequently criticized for not playing a leading part in the social, civic, and political problems of his community. To remedy it may require more than one measure, but it appears to this author that the first step in effective preparation for such leadership is for the engineer to understand the psychology of himself and his fellowmen. That done, a course in sociology, or government, or economics, and so forth, may be added if time permits. In any case, if the graduate is well grounded in the general principles of human behavior and relationships and has had some systematic practice in college, he can obtain later, by private study, any additional knowledge needed for the civic activity into which he may wish to enter effectively.

Life has many surprises, and we may at any time be thrown into unexpected problem-situations. In such cases, we may count on the engineer to solve the

technical problems involved, even though they may be far outside of his specialty and we may fear his failing on account of mismanagement of the human problems involved, unless he has had special training or was born with an instinct for the human equation. War is such a situation.

At the AIEE Northeastern District meeting in Pittsfield (April 1943), Colonel Beukema told us that the reports received from the officers in the field indicate that the soldiers with cultural training make better leaders, and therefore the Army specialized training program is making some provision for such training.⁴ I understand that the Navy program is even more generous in this respect. While I do not know whether the Army or the Navy has made any appraisal of the value of different cultural courses for its purposes, the type of basic cultural training here advocated would seem to be superior to classics, philosophy, and so forth, for the fighting man.

Problem of Time and Place

The minimum cultural training advocated here can certainly be had in the time now allotted for the humanities. It appears to this writer, however, that those who are particular about the nature and quality of such training are likely to ask for more of it and for some additional subjects, thereby prolonging the curriculum by another half year or full year. In normal times and the long run, I think the student is likely to be well repaid for the extra time. A five-year curriculum for the engineer is not unreasonable compared with the seven years many chemists are putting in now (to secure a degree of doctor of philosophy), the eight years that physicians generally put in, and the five to seven years that the requirements of some of the graduate schools of engineering entail.

As to the place, as things stand now, some students may find it necessary to consider the advisability of dividing their time between two institutions, one for the cultural courses, the other for engineering, especially if an extra year is to be devoted to the purpose. This naturally raises questions of loyalty and the difficulty of achieving advanced positions in the social and extracurricular activities in either institution, which in their turn work contrary to the major goal. I think certain arrangements have less objectionable features than others. The most proper solution of the problem is that the cultural curricula of the engineering schools be made as efficient as their engineering curricula.

Electronically Controlled Dry-Disk Rectifier

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IN spite of the practically universal use of alternating current for power generation and distribution, there exists an ever-increasing demand for direct current. To obtain direct current from the available supplies of alternating current, means of rectifying the alternating current have been developed. While many types of equipment are available, three types, each supreme in its own range, are found to be in general use for heavy-duty d-c power applications. The mercury arc has proved most efficient for the higher voltages from 250 volts on up. The intermediate range from 60 volts to 250 volts is supplied by the motor generator set. In comparatively recent years the low-voltage range from 0 to 60 volts has been taken over more and more by dry-plate rectifiers.

The dry-plate rectifier was first introduced approximately 30 years ago when the copper-sulfide rectifier was developed. Later in the early 1920's the copper-plate rectifier was brought out. Recently, in fact during the last four years, selenium-oxide rectifiers have found wide usage in American industry. The selenium rectifier was developed and introduced in Europe in 1928. Continental acceptance of this rectifier has been widespread, for latest estimates indicate that 83 per cent of the metallic-junction rectifiers in use abroad are selenium.

Rectifier Characteristics

The selenium-oxide rectifier has much to offer in the way of stability, efficiency, economy, dependability, compactness, light weight, and ability to take heavy overloads for periods of short duration. Within the lower-voltage range it compares more than favorably with rotating equipment.

Similar to most electrical equipment, selenium rectifiers are designed for a temperature rise in continuous operation of 40 degrees centigrade above an ambient

of 35 degrees centigrade. This means that up to the ultimate temperature there is no theoretical limit upon current handling capacity, and, consequently, the rectifier has the ability to handle large overloads for a short interval. The principle components of the selenium rectifier are transformers, selenium stacks, and bussing. These are all static elements, each of which has an indeterminately long life. Because of this freedom from moving parts, bearings, and commutators, the dry-plate rectifier offers completely dependable maintenance-free operation. Selenium stacks readily lend themselves to compact space design and even the largest rectifiers require no foundation.

The low forward resistance and high reverse resistance of the selenium stack combine to give the rectifier excellent economy and efficiency. Power tests show rectifier efficiencies of between 65 per cent and 85 per cent, depending upon the circuit and the load. The forward resistance of the stack is an inverse function of the stack current. Consequently, the I and R loss will tend to remain constant, and the rectifier will maintain high efficiency with unusual consistency from 20 per cent to 150 per cent of full load. In the larger equipment the efficiencies of rotating equipment compare with that of the selenium rectifier at full load, but the efficiency of rotating machinery drops rapidly as the load deviates from full load.

It is only in the matter of control and regulation of the output voltage that the average large selenium rectifier is sur-

passed by rotating equipment. Normal no-load to full-load voltage regulation for selenium rectifiers is 10 per cent to 18 per cent. While such regulation is satisfactory for most applications, there is still a great number of installations which require closer voltage control and regulation over a wide range. It was to meet this need that the fully automatic electronic control discussed in this article has been developed. The control makes it possible to obtain output voltages constant to one half of one per cent from selenium rectifiers even when the rectifier is subjected to widely varying loads and large changes in input line voltage. The design of the control is such that it can be used on either large or small rectifiers without any circuit changes.

Regulated Rectifier Basic Elements

The basic elements of a regulated rectifier (Figure 1) are a critically designed filter, a source of constant d-c potential, a high-gain d-c amplifier, thyatron-controlled saturating reactors and the selenium-oxide-rectifier disks with their associated transformers. In brief, the operation of these sections is as follows: The d-c voltage output of the selenium rectifier is passed through a filter to eliminate the a-c ripple and then compared against a constant d-c potential. This difference between the filtered rectifier voltage and a constant potential is applied to the grid of a high transconductance tube used as a d-c amplifier. Such circuiting gives relatively large d-c voltage changes from the amplifier for small changes in rectifier voltage. These changes in amplified direct current are used to form the basis for a d-c phase-shifting network that controls the grids of a pair of thyratrons. The regulated output of the thyratrons is circulated through the secondary windings (connected in series with proper phase relationship so that reflected primary voltages cancel)

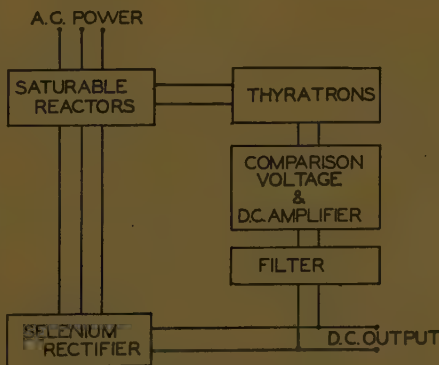


Figure 1. Block diagram

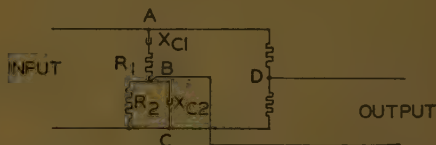


Figure 2. Filter circuit to eliminate ripple from d-c output voltage before comparing against fixed voltage

f = fundamental ripple frequency

$$X_{C1} = \frac{1}{2\pi f C_1}$$

$$X_{C2} = \frac{1}{2\pi f C_2}$$

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of saturating reactors that are in turn in series with the primary windings of the rectifier power transformers. The components of the control are sequenced so that if, for example, an increase in load were to tend to lower the rectifier voltage, the decrease in voltage would be amplified and used to shift the thyatron grids forward to cause greater saturating current to flow through the reactors decreasing the drop across the reactors and increasing the voltage across the power transformer.

Filter Design

One of the greatest single problems encountered in the development of the successful circuit was that of a suitable filter for the potential taken from the rectifier output to actuate the control. Because of the necessity for using a comparison voltage and an amplifier, even the small a-c ripple present in the output of a three-phase selenium rectifier is amplified enough, if applied directly without filtering, to render the phase-shifting circuit of the thyatron completely inoperative. The commonly used reactor-capacitor filters were found to be impractical. Their extremely high time constants make it impossible for such filters to follow rectifier voltage variations very closely with the result that they cause the rectifier to hunt and oscillate. The filter required therefore was one with a very high a-c attenuation factor, practically no d-c attenuation, and an extremely low time constant. The answer was found to lie in a variation of the Wien bridge (Figure 2).

By proper selection of constants it is possible to have the a-c voltage from *B* to *C* equal in phase and magnitude to the a-c voltage from *D* to *C*. As these vectors then subtract, the a-c potential from *B* to *D* equals zero. Resistance R_2 across X_{C2} acts to keep the d-c potential between *B* and *C* equal to zero. To hold the d-c attenuation at a minimum, X_{C1} should be very small as compared to X_{C2} ; however, any decrease in X_{C1} will result in an increase in the time constant of the filter. The constants of the filter may be calculated and curves computed for the lowest possible time constant by use of the following equations:

$$Z_{BC} = \frac{R_2 X_{C2}^2}{R_2^2 + X_{C2}^2} - j \frac{X_{C2} R_2^2}{R_2^2 + X_{C2}^2} = R_{BC} - jX_{BC}$$

As the voltage across *BC* must be in phase with the voltage across *AB*,

$$R_1/R_{BC} = X_{C1}/X_{BC}$$

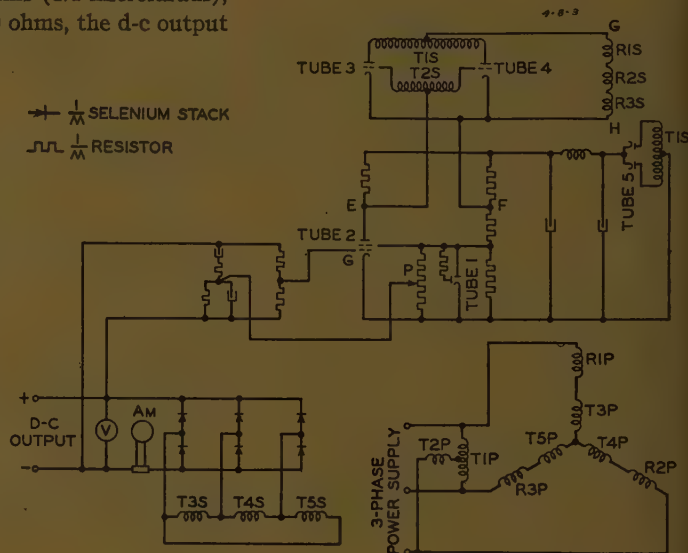
The time constant of the filter is a function of C_1 and the resistance in series with it, that is, $R_1 + R_2$:

$$\text{Time constant} \propto C_1(R_1 + R_2)$$

For example, if in a three-phase full-wave rectifier whose fundamental ripple frequency is 360 cycles, $R_1 = 100$ ohms, X_{C1} equals 100 ohms (4.4 microfarads), and R_2 equals 2,000 ohms, the d-c output

Figure 3. Simplified control circuit

T1P—Transformer 1 primary winding
T1S—Transformer 1 secondary winding
R1P—Saturable reactor 1 primary winding
R1S—Saturable reactor 1 secondary winding



of the filter will be approximately 91 per cent of its input. If the time constant were to be cut in half by changing X_{C1} to 200 ohms (2.2 microfarad), the output of the filter would still be approximately 83 per cent of input.

Comparison Voltage and Amplifier

The output voltage of the filter is compared with a constant voltage obtained from potentiometer *P* (Figure 3), and the difference is applied to the grid of tube 2 for amplification. As we are taking the difference between two voltages, small changes in filter voltage mean relatively large percentage changes in the tube grid potential. For example, if the filtered voltage were 25 volts and the constant comparison voltage 24 the difference or applied grid voltage would be one volt. Now if the filtered voltage increases four tenths of one per cent to 25.1 volts the grid voltage increases to 1.1 volts which, of course, is an increase of ten per cent. The variations in grid voltage of tube 2 cause it to act as a variable resistance. The changes in internal resistance of the tube will naturally cause changes in the voltage drop across the tube. These voltage changes are such as to tend to limit the voltage amplification obtained. However, beam power tubes or pentodes which are little affected by plate voltage give excellent results. By operating tube 2 with a low screen grid

potential which is maintained constant and proper choice of load resistance it is possible to obtain d-c voltage amplification of 20 to 30 decibels with one tube.

The constant voltage used for comparison against the filtered potential can be obtained by several methods. Probably the simplest source can be found in

gaseous regulator tubes. Such tubes are readily available and are produced today with excellent characteristics and long life. The regulator tube shown as tube 1 in Figure 3 supplies constant voltage for two purposes. As the screen current of tube 2 will tend to vary with changes in grid voltages, additional amplification and stability is obtained by using the constant drop across tube 1 for the screen grid bias of tube 2. A potentiometer *P* bridged across the regulator tube provides the constant voltage to be compared against the filtered output. The potentiometer is the means by which the control is set for any desired rectifier output potential.

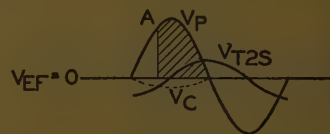


Figure 4A. Phase relations of thyratrons with d-c component of grid voltage equal to zero

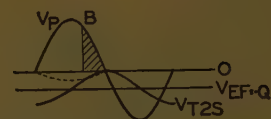


Figure 4B. Phase relations of thyratrons with d-c component of grid voltage equal to negative quantity

V_P —Thyatron anode voltage
 V_{T2S} —A-c component of thyatron grid voltage
 V_{EF} —D-c component of thyatron grid voltage
 V_C —Critical thyatron firing voltage

Phase-Shifting Network

As the internal resistance of tube 2 can be varied from extremely high values to very low ones, the potential across EF (V_{EF}) can be swung from positive through zero to negative. V_{EF} combined with the a-c output of transformer T_2 forms a d-c phase-shifting network that controls the grids and consequently the output of the thyatron, tubes 3 and 4. The voltage across the secondary winding of transformer 2 has been shifted 90 degrees with respect to the secondary winding of the plate transformer of the thyatrons,



Figure 5. Single-phase network to obtain voltages shifted 90 degrees with respect to reference voltage

X_C is much greater than R

transformer 1. If V_P is the plate voltage of one of the thyatrons, and V_{T2S} is the grid voltage, Figure 4A shows that with $V_{EF}=0$ the grid-voltage curve intersects the critical grid curve at the point A where the tube fires and conducts current until $V_P=0$. However, if V_{EF} is equal to a negative quantity, Figure 4B, the tube will not fire until point B and will conduct correspondingly less than when $V_{EF}=0$. When V_{EF} goes positive, the critical grid voltage is intersected sooner, and more current is passed. The 90-degree phase shift required for V_{T2S} may be obtained by two methods. For single-phase operation (Figure 5) the primary winding of transformer 2 is connected in parallel with a resistance and both the transformers and the resistance are in turn connected in series with a capacitor. By making the impedance of the capacitor considerably more than that of the resistor, the current through the circuit can be made leading by almost 90 degrees. If this holds, then the voltage drop across the resistor, and consequently $T2P$ will be shifted 90 degrees also. For three-phase operation the voltage shift between $T1$ and $T2$ is conveniently obtained by using the Scott connection for converting three-phase power to two-phase (Figure 6).

Saturating Circuit

Tube 3, tube 4, and transformer 1 form a controlled rectifier, the output of which is used to saturate the reactors $R1, R2$, and $R3$. The primary windings of

these reactors are in series with the primary windings of the power transformers $T3, T4$, and $T5$. The secondary windings of the reactors are connected so that the a-c voltages induced from their primary windings are subtractive, and the a-c potential from G to H equals zero. The division of voltage across the primary windings of the reactors and transformers is a function of the reactance of the reactor, the secondary loading of the reactor, the reactance of the transformer, and the secondary loading of the transformer. The reactances of the elements are determined by their physical characteristics, namely, the number of primary turns and lengths, area, and composition of the magnetic path. The secondary loading of the transformer consists of the rectifier stacks and the rectified power load. The control of the entire unit is obtained from the secondary loading of the reactors, which is, of course, the d-c saturating current. Amazingly large amounts of power may be controlled over wide voltage ranges by comparatively small amounts of saturating power. For example, 1,500 watts of rectified direct current is being handled in a small installation by 50 watts of saturating power.

From the designer's standpoint the most difficult problem is that of determining reactor sizes to meet voltage specifications under no-load conditions. This is



Figure 6. Three-phase network to obtain voltages shifted 90 degrees with respect to reference voltage

particularly true in cases where there are large fluctuations in line voltage or where wide-range voltage control is desired. Using the simplest type of series circuit shown in Figure 3, the no-load output voltage may be controlled from one-half to full voltage when the reactance of the reactor is equal to the reactance of the power transformer. Economically, it is not practical to try to obtain more than 50 per cent voltage control with the circuit shown. However, by proper circuiting it is possible to obtain zero to full voltage control without having to resort to the use of tap switches.

Performance

Although capable of extremely close control, the circuit as shown in Figure 3 is quite simple and uses relatively few

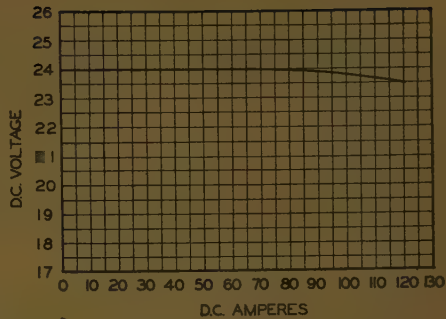


Figure 7. Performance curve of 100-ampere 24-volt electronically controlled selenium rectifier

vacuum tubes. Tubes were chosen with large cathode areas and are operated well below their rated output resulting in extremely long service life. Tube 5 is a rectifier tube supplying direct current for the amplifier tube 2. In controls for most industrial installations this tube would be replaced by a small selenium-oxide high-voltage bridge rectifier.

Figure 7 is a graph showing the voltage regulation underload of a controlled selenium rectifier which is being used for aircraft "transceiver" testing. The specifications call for a 100-ampere rectifier capable of having its output voltage varied smoothly from 20 volts to 30 volts and having very fine no-load to full-load voltage regulation at a normal operating point of 24 volts. The curve given was obtained with a primary power supply that had a five per cent to ten per cent voltage drop at full load. While a slightly drooping voltage characteristic is usually desired, the circuit may be changed so that the rectifier exhibits either a constantly rising voltage or else a voltage characteristic similar to that of a compound generator. One very satisfactory method of obtaining an output voltage that is a function of the output current is that of inserting a current transformer in the a-c primary power supply of the rectifier. The output of the current transformer is then rectified, filtered, and fed with proper polarity into the control circuit between the Wien bridge filter output and the comparison voltage.

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Electric Circuits and the Magnetic Compass

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Synopsis: This paper will endeavor to show the deviations in the airplane magnetic compass caused by electromagnetic effects from the ship's wiring and will suggest some means that can be used to correct them.

GLOBAL warfare has extended the field of operations of aircraft beyond radio beams, landmarks, highways, and beacon lights, and, hence, has made the magnetic compass of paramount importance. Because of steel structures, armor plate, and single-wire electric circuits which carry increasingly larger currents, the magnetic disturbances at the conventional compass location have increased to such an extent that several remote indicating types of compasses have had to be developed.

The marked trend in the use of remote indicating types of compasses has created a shortage in these instruments. One of the purposes of this paper is to point out some of the problems created in the design of the air frame that can be solved by certain design techniques and the application of basic electromagnetic principles, thereby restoring the usefulness of direct-reading compasses and improving the accuracy of the remote indicating types. The scope of this paper will be limited to electromagnetic disturbances since the subject of ferromagnetism involving soft-iron effects, residual magnetism and its control in design and manufacturing processes, and other allied problems is too far-reaching to be treated other than in a separate paper. It can be noted that highly satisfactory results have been attained at Lockheed-Vega in the control of the ferromagnetic properties of air frames, both through design and demagnetizing processes during manufacture.

Aircraft electric systems conventionally utilize d-c generators, motors, and storage batteries. Certain limited applications of

alternating current are found wherein 400-cycle inverters are utilized to supply small quantities of power for autosyn and similar transmitters, as well as for certain radio applications. However, the d-c supply and field winding of these inverters often cause noticeable magnetic disturbances. Furthermore, as a weight-saving measure, the air frame has been used as a

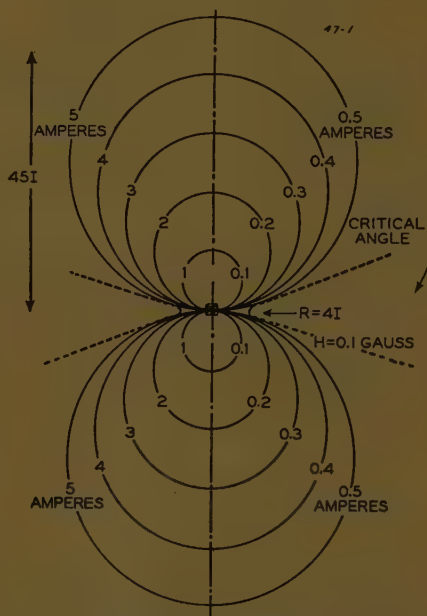


Figure 1. Horizontal wire-placement pattern for $H=0.1$ gauss. $D=1$ degree

ground return, leaving the electromagnetic field surrounding the single "hot wire" with little, if any, neutralizing field from a parallel ground-return conductor. Until the air frame is fitted with sources of alternating current to the exclusion of direct current, this problem must be faced by the electrical designer in his work on air frame electric systems and equipment.

The magnetic field in which the compass functions is extremely weak in comparison with the electromagnetic fields involved in power applications. The directive force utilized by the compass is the horizontal component of the earth's field, and this varies greatly over the surface of the earth, being zero at the magnetic poles and increasing to a maximum of approximately 0.40 gauss at the mag-

netic equator. When it is pointed out that the horizontal component of the earth's field along the North Atlantic ferry route varies between 0.15 and 0.10 gauss, it becomes apparent that a rather weak field surrounding a single-wire conductor in an air frame can cause deviations of a serious nature. Even in modern combat aircraft the remote indicating transmitter, located as favorably as possible, is subject to serious errors from this source. Since space limitations in aircraft dictate compass locations, and since the electric conductors must be located within the fuselage and wing surfaces, some serious problems arise that must be solved by ingenious electrical design.

The accepted practice in treating magnetic-compass problems is to resolve the magnetic field in question into two components: the horizontal component, which produces a directive force on the compass, and the vertical component, which has no directive force under normal conditions. Since the directive force is confined to the

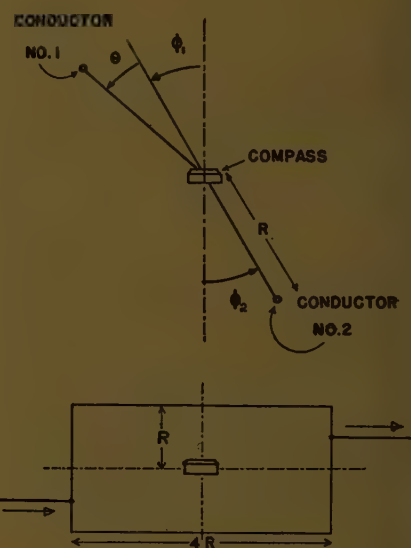


Figure 2. An illustration of angular asymmetry in split-wire neutralization

horizontal component of the magnetic field at the compass location, it will be affected only by the horizontal component of the magnetic field produced by any electric circuit. Any electric circuit may be separated into finite sections, and, if well-known electromagnetic formulas are used, the field at the compass location can be calculated for each section. These fields combined vectorially will give the components of the electromagnetic field caused by the electric circuit. Of course, it is the resultant horizontal component which directs the compass, and this will vary, not only with the intensity of the earth's field and the current flowing in

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each electric circuit, but also will change with each heading of the aircraft.

This deviation cannot be corrected by means of the regular compass compensator, and to allow for it in navigation would require a book full of deviation cards; consequently, these effects must be reduced to a certain allowable maximum. For example, in Southern California, where the horizontal component of the earth's field is 0.26 gauss, a certain current causes a deviation equal to plus two degrees, whereas the same current causes plus four degrees deviation in more northerly magnetic latitudes, and if the current increases the deviation will increase still further.

Present Air Force standards, as to deviation tolerances, are based on a horizontal component of the earth's field of 0.18 gauss, and a vertical component of 0.54 gauss, but, with aircraft operation increasing in northerly latitudes and transpolar air transportation a near actuality, the electrical designer can well anticipate a narrowing of the tolerance limits for compass deviations. Table I sets forth

Table I. Calculated Distances, R, of Compass From Long Straight Conductor to Give Compass Deviation, D, of One Degree. Earth's Horizontal Magnetic Field in Gauss = H

Current		Distance for Deflection of One Degree					
		H=0.1		H=0.180		H=0.264	
Ampere	Abampere	Centimeters	Inches	Centimeters	Inches	Centimeters	Inches
0.1	0.01	11.4	4.5	6.34	2.5	4.32	1.7
0.2	0.02	22.8	9.0	12.68	5.0	8.64	3.4
0.3	0.03	34.2	13.5	19.0	7.5	12.9	5.1
0.4	0.04	45.6	18.0	25.4	10.0	17.3	6.8
0.5	0.05	57.0	22.5	31.7	12.5	21.6	8.5
1.0	0.1	114	45.0	63.4	25.0	43.2	17.0
2.0	0.2	228	90.0	126.8	50.0	86.4	34.0
3.0	0.3	342	135.0	190.0	75.0	129.0	51.0
4.0	0.4	456	180.0	254.0	100.0	173.0	68.0
5.0	0.5	570	225.0	317.0	125.0	216.0	85.0
10.0	1.0	1,140	450	634	250	432	170
20.0	2.0	2,280	900	1,268	500	864	340
30.0	3.0	3,420	1,350	1,900	750	1,290	510
40.0	4.0	4,560	1,800	2,540	1,000	1,730	680
50.0	5.0	5,700	2,250	3,170	1,250	2,160	850

the calculated distances of a long straight horizontal conductor in a vertical plane above or below a compass location at which a deviation of one degree will be created by the currents designated for the three values of the earth's horizontal components shown.

The notable changes in these distances caused by weaker horizontal components of the earth's field and increasing currents are of serious importance. A useful family of curves, shown in Figure 1, can be plotted by drawing circles with their centers on a vertical line through the compass location, tangent to the compass location with diameters equal to these distances. If a long horizontal north-

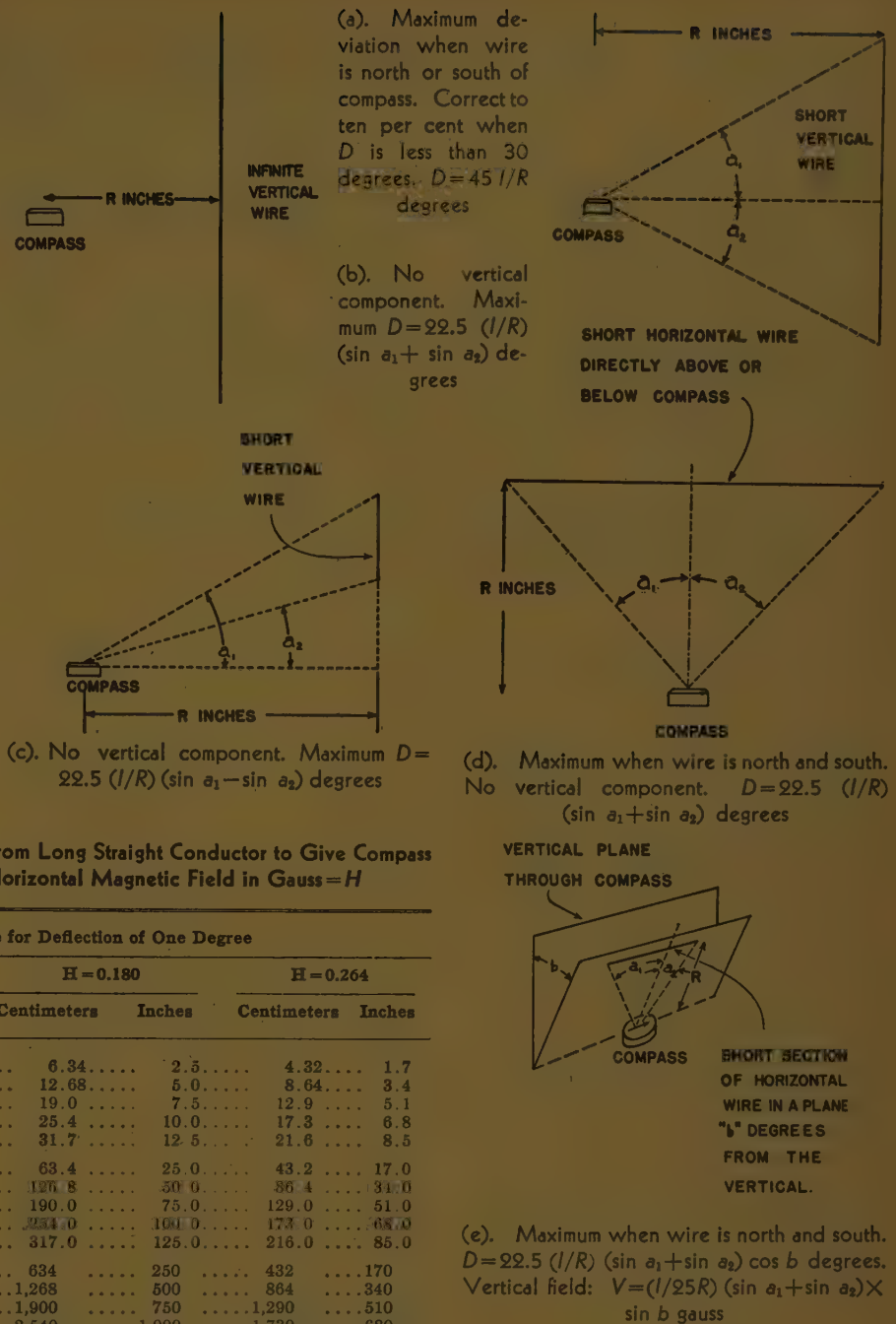


Figure 3. Compass deviations caused by straight conductors. H=0.1 gauss

south conductor is placed directly above or below the compass at a distance equal in inches to 45 times the current in amperes, then the deviation will be plus or minus one degree when the horizontal component of the earth's field is 0.10 gauss. This conductor can be placed anywhere on the circle with the same horizontal component at the compass if the current and direction remain the same. Where these curves approach the compass location, positioning of the conductor becomes quite critical to slight vertical displacements, and allowance should be made for possible changes in the position of either the compass or the conductor.

Figure 1 suggests a neutralizing tech-

nique where the removal of the conductor to a safe distance or the installation of a return ground wire is not desirable. The technique employs a division of the circuit between two parallel conductors. Each one is placed on its circle, one above and one below the compass location. By extending the split circuit a distance of four times the diameter of the circle used, 90 per cent of the disturbance will be neutralized. The use of this method will be confined to sections of the air frame which will give the necessary length and symmetry for properly aligning the conductors, such as in the fuselage, boom, or wing. Where space does not permit equal distances in each direction from the

compass location, the current can be split in proper portions by varying the wire cross section so that the conductors will fall on appropriate current circles. It should be noted further that, although the horizontal components of the two split conductors will be equal and opposite, the vertical components will not be equal and opposite unless the conductors are diametrically opposite. However, the vertical components can be added vectorially, and should the resultant exceed values to be discussed subsequently, an effort should be made to achieve complete symmetry.

Table II. An Example of Angular Tolerances for Split-Wire Neutralization

Data: $R=36$ inches, $H=0.100$ gauss, $I=10$ amperes, $D=1$ degree

ϕ_1^*	θ	
0 degrees.....	+24 degrees 25 minutes.....	-24 degrees 25 minutes
10 degrees.....	+16 degrees 27 minutes.....	-24 degrees 25 minutes
20 degrees.....	11 degrees 46 minutes.....	-24 degrees 25 minutes
30 degrees.....	9 degrees 3 minutes.....	-18 degrees 40 minutes
40 degrees.....	7 degrees 26 minutes.....	-9 degrees 16 minutes
50 degrees.....	6 degrees 24 minutes.....	-7 degrees 25 minutes
60 degrees.....	5 degrees 46 minutes.....	-6 degrees 14 minutes
70 degrees.....	5 degrees 22 minutes.....	-5 degrees 50 minutes
80 degrees.....	5 degrees 11 minutes.....	-5 degrees 30 minutes
90 degrees.....	5 degrees 8 minutes.....	-5 degrees 22 minutes

* ϕ_1 may be + or -, but, as ϕ_1 changes sign, θ values must also change sign. See Figure 2.

When it is impossible to arrange the two wires of the split-wire system in perfectly symmetrical positions, it is possible to allow relatively large amounts of asymmetry as to angle and still have a resultant field producing less than one-degree deviation of the compass. The angle of tolerance depends upon the distances, the current, and the position angle of the conductors, as shown in Figure 2. The tabulated values in Table II are obtained from the formula $B_2-B_1=0.072 (I/R) [\cos \phi - \cos (\phi \pm \theta)]$, where B_1 and B_2 are the horizontal fields at the compass of conductors 1 and 2. For example, Table II illustrates a 20-ampere conductor which has been split at a distance of $4R$ with each leg carrying ten amperes and R taken as 36 inches.

After the horizontal component has been considered, the vertical component should be examined. A current-carrying conductor can lie precisely in a horizontal plane passing through the compass, and no horizontal component will exist to cause deviation of the earth's field. However, a vertical component of considerable intensity can exist, which, if excessive, can cause the compass card to dip into the vertical field. More important, however, is the resultant horizontal com-

ponent that occurs when the aircraft changes attitude from horizontal flight position, either by "roll" or by changes in angle of attack due to loading or other causes. For instance, consider a circuit which produces only a vertical field of 0.020 gauss at the compass location in flight attitude A . Now, let the flight attitude change to B , differing by five degrees from A . The former vertical field will now have a horizontal component equal to 0.00175 gauss which, over the North Atlantic, would produce a deviation of one degree. This vertical field of 0.020 gauss is produced at a hori-

zontal distance in inches equal to four times the current in amperes. That is to say, if 40 inches from a horizontal wire carries ten amperes, the field is 0.020 gauss. From the foregoing it would seem that a desirable compass-performance standard would be to limit the permissible deviation to one degree where the horizontal component of the earth's field is 0.10 gauss.

Figure 3 has been prepared to permit easy calculations where data are in inches, amperes, and degrees instead of centimeter-gram-second units. The formulas give the compass deviation D in degrees caused by straight conductors in various relationships to the compass location. All are based on a horizontal component of the earth's field of 0.10 gauss.

A complete compensation of any one circuit is possible by means of a compensating coil which carries the current equal or proportionate to the current in the disturbing circuit and is placed so that the magnetic field of this coil supplies a flux at the compass location which is exactly equal in magnitude and opposite in direction to the combined disturbance at that location of all the rest of the circuit.

The disturbance which will be caused by any single-wire circuit can be approxi-

mated from electromagnetic formulas by taking the circuit in sections, but it is far more satisfactory to measure the disturbance with a magnetometer in a finished airplane. The principle reason for the unsatisfactory solution arrived at by the mathematical treatment alone is that the return circuit through the air frame is not uniform, but is distorted by joints in the skin, extrusions attached to the frame, openings, and even magnetic fields. However, a direct measurement is relatively easy to make by use of a good magnetometer. The airplane is placed in flight attitude on a north magnetic heading, and the magnetometer pickup element is placed in the compass location so oriented that it will measure a horizontal component of the earth's field along the axis of the ship. The circuit in question is then switched on and off, and the magnetometer readings are taken for both field strengths. The difference gives the magnitude of this axial component of the disturbing electromagnetic field. The magnetometer pickup element is next oriented horizontally crosswise of the ship, and the same procedure is repeated. The third observation is made with the axis of the magnetometer vertical, and from these three components it is quite easy to determine the direction and magnitude of the disturbing flux. A small series coil may then be arranged in the neighborhood of the compass so that the field produced by this coil will, at the compass location, be equal and opposite to that produced by the circuit causing the disturbance. The coil then should be installed, and the result should be checked on all three axes with the magnetometer.

From the foregoing it is evident that the electric circuits necessary to the operation of the airplane are the cause of many compass errors. It is further seen that these errors can be anticipated by calculation from the geometry of the ship's wiring, and that the wiring can be rearranged so that the errors will be reduced to a negligible quantity, or, where it is not possible to move the wiring, it may be possible to find a solution by using double conductors, or coaxial conductors, or even by dividing the circuit into symmetrical paths. It is further shown that it is possible to compensate for the disturbance caused by any given electric circuit by the use of a series compensating coil, pre-calculated and properly oriented, to cancel out all components of the disturbing flux at the compass location.

Asymmetrical Loading of Three-Phase Three-Winding Transformer Banks

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Synopsis: It is accepted USSR practice to carry three-phase industrial load and single-phase traction load on a single three-phase three-winding transformer. For a given combination of loads it is necessary to determine the proper capacity relationships of the three windings.

This paper presents an analysis of the problem by the methods of symmetrical components. The data obtained from this analysis were used in setting up the standards for selection of transformer size for combined three-phase industrial and single-phase traction loading.

THE problem of unbalanced loading of three-phase transformer banks is of practical importance both in industrial installations where single-phase equipment, such as welders, is supplied and in railway installations where single-phase traction loads are fed from industrial three-phase banks. The present investigation deals only with the case of single-phase traction loading.

Since combination of symmetrical three-phase industrial load, and single-phase traction loading on three-phase transformer banks is no different from other types of asymmetrical loading, the solution to the one problem may be applied to all cases of asymmetrical loading practice.

The condition studied is that of the three-phase bank of three-winding single-phase transformers loaded asymmetri- cally. The transformer winding connections would be as follows:

1. The primary winding would be wye-connected with the neutral grounded.
2. The secondary winding would be delta-connected for symmetrical three-phase load- ing.
3. The tertiary winding would be wye-connected with the neutral ungrounded for asymmetrical loading.

The most frequent type of loading for traction circuits is the two-phase asym-

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metrical loading such as is shown in Figure 1.

In the solution of the problem of the capacity relationships of the separate windings, it is necessary to determine current distribution in the windings and effective voltage. The effect of magnetizing current is neglected.

The solution is for the equivalent star circuit as shown in Figure 2. The effective impedances of the separate branches of the circuit corresponding to the impedances of the transformer phase windings are

$$Z' = \frac{Z_{12} + Z_{31} - Z_{23}}{2} \quad (1)$$

$$Z'' = \frac{Z_{23} + Z_{12} - Z_{31}}{2} \quad (2)$$

$$Z''' = \frac{Z_{31} + Z_{23} - Z_{12}}{2} \quad (3)$$

where Z' , Z'' , and Z''' represent the effective impedances of the branches of the equivalent circuit as shown in Figure 2, and Z_{12} , Z_{13} , and Z_{23} , represent the leakage impedances between windings as obtained from short-circuit tests.

The current distribution may be determined by the application of symmetrical components. In so doing, it is necessary to consider the internal impedances of the system. Refer again to the circuit of Figure 1, and if the neutral remains ungrounded, the asymmetrical loading has no zero-sequence current components, that is, $I_0 = 0$.

The current and voltage relationships for the circuit may be represented by the positive- and negative-sequence components

$$\dot{I}_a = \dot{I}_1 + \dot{I}_2 \quad (4)$$

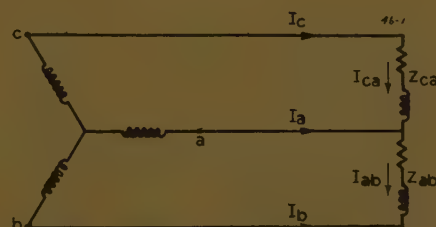


Figure 1. Method of connection of asymmetrical traction load to the star-connected secondary of a three-winding transformer

$$\dot{I}_b = a^2 \dot{I}_1 + a \dot{I}_2 \quad (5)$$

$$\dot{I}_c = a \dot{I}_1 + a^2 \dot{I}_2 \quad (6)$$

and

$$\dot{V}_a = \dot{V}_1 + \dot{V}_2 \quad (7)$$

$$\dot{V}_b = a^2 \dot{V}_1 + a \dot{V}_2 \quad (8)$$

$$\dot{V}_c = a \dot{V}_1 + a^2 \dot{V}_2 \quad (9)$$

where $\dot{V}_1$ and $\dot{V}_2$ are the positive- and negative-sequence components of the voltage drop across the impedance of the external asymmetrical loads. Considering equations 4 through 9, equations for the circuits based on Kirchhoff's second law may be written as

$$\dot{I}_a = \dot{I}_1 + \dot{I}_2 = \frac{\dot{V}_1(1-a^2) + \dot{V}_2(1-a)}{Z_{ab}} + \frac{\dot{V}_1(1-a) + \dot{V}_2(1-a^2)}{Z_{ac}} \quad (10)$$

$$\dot{I}_b = a^2 \dot{I}_1 + a \dot{I}_2 = \frac{\dot{V}_1(a^2-1) + \dot{V}_2(a-1)}{Z_{ab}} \quad (11)$$

$$\dot{I}_c = a \dot{I}_1 + a^2 \dot{I}_2 = \frac{\dot{V}_1(a-1) + \dot{V}_2(a^2-1)}{Z_{ac}} \quad (12)$$

These equations, including the unknowns, $\dot{I}_1$, $\dot{I}_2$, $\dot{V}_1$, and $\dot{V}_2$, are not sufficient to complete the solution of the problem. To obtain the necessary additional conditions, it is necessary to determine the internal impedance components Z_0 , Z_1 , and Z_2 of the transformer windings.

Since it has been assumed that the applied primary potential is symmetrical, its zero- and negative-sequence components will be equal to zero. It follows that the effective electromotive force in the system of zero sequence and negative sequence will be zero, also, while in the positive-sequence system the electromotive force will be $\dot{V}_\phi$. These relationships may be expressed as

$$0 = \dot{I}_0 Z_0 + \dot{V}_0 \quad (13)$$

$$\dot{V}_\phi = \dot{I}_1 Z_1 + \dot{V}_1 \quad (14)$$

$$0 = \dot{I}_2 Z_2 + \dot{V}_2 \quad (15)$$

to show the relationship of the effective electromotive forces of any system and the voltage drops in the internal and external impedances of the system.

Solution of the equations 10 to 15, inclusive, is in the form of

$$\dot{I}_1 = \frac{\dot{V}_\phi (Z_{ab} + Z_{ac} + 3Z_2)}{Z_{ab}Z_{ac} + (Z_1 + Z_2)(Z_{ab} + Z_{ac}) + 3Z_1Z_2} \quad (16)$$

and

$$\dot{I}_2 = \frac{-\dot{V}_\phi \left(Z_{ab}a + \frac{Z_{ac}}{a} \right)}{Z_{ab}Z_{ac} + (Z_1 + Z_2)(Z_{ab} + Z_{ac}) + 3Z_1Z_2} \quad (17)$$

where

- I_1 = positive-sequence current
- I_2 = negative-sequence current
- Z_1 = positive-sequence impedance of the whole equivalent circuit
- Z_2 = negative-sequence impedance of the whole equivalent circuit
- Z_{ab} and Z_{ac} = impedance of the asymmetrical loads with reference to the primary winding as obtained from

$$Z_{ab} = \frac{V^2}{P_{ab}} (\cos \theta + j \sin \theta) \quad (18)$$

where

- V = primary interphase voltage in kilovolts
- P_{ab} = capacity of the corresponding branch of the circuit, in megavolt-amperes
- $\cos \theta$ = power factor of the asymmetrical load

Table I. Load Distribution and Capacity Relationship for the Most-Loaded Phase of a Three-Winding Transformer With Asymmetrical Loading

Case Num- ber	Asym- metrical Load		Ratio of Asym- metrical Load to Total Load Per Cent	Winding Loads of the Transformer for the Most-Loaded Phase "a"				Winding Capacity Relationship According to Standard OCT 2,524 (Per Cent)			
	Megavolt- Amperes	Sym- metrical Load Megavolt- Amperes		Tertiary (Single- Phase Traction)		Secondary (Three- Phase Regional) Megavolt- Amperes	Estimated Primary Megavolt- Amperes	Ter- tiary	Sec- ondary	Pri- mary	
				Per Cent Primary	Per Cent Primary						
											P _{ab}	P_{ao}
1	9.9	8.6	4.9	79	10.7	99	1.85	10.80	100	67	100
2	9.9	8.6	9.3	67	10.7	82	3.10	13.00	67	67	100
3	9.9	8.6	15.0	55	10.7	75	5.00	14.35	67	67	100
4	9.9	8.6	22.0	46	10.7	63	7.35	16.85	67	67	100
5	8.8	4.6	5.9	70	7.8	91	1.96	8.45	67	67	100
6	8.8	4.6	13.4	50	7.8	70	4.57	11.02	67	67	100

The internal, or applied negative-sequence impedance of the system includes also the impedance of the symmetrical load taken for the corresponding branch of the circuit

$$Z_p = \frac{V^2}{P_p} (\cos \beta + j \sin \beta) \quad (19)$$

where $\cos \beta$ is the power factor of the symmetrical load.

Since the positive- and negative-sequence impedances of the transformer are equal, Z_1 and Z_2 , the impedances of the whole equivalent circuit will differ only by the difference between the positive and negative sequence impedances of the symmetrical load in the secondary delta winding.

To bring the total impedance in the positive- and negative-sequence system up to the point at which the asymmetrical load is to be applied, it is necessary to include the impedance of the parallel paths, both primary and secondary. This is expressed by

$$Z_a = \frac{Z'(Z_p + Z'')}{Z' + Z_p + Z''} + Z''' \quad (20)$$

referred to in Figure 3.

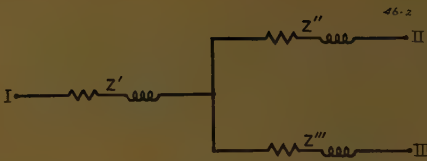


Figure 2. Equivalent star circuit of a three-winding transformer

By use of the principle of superposition, electromotive forces are assumed to be applied at this point, feeding the system by the positive- and negative-sequence currents. The effective negative-sequence voltage at the primary-winding terminals may be considered to be zero.

To establish the true current distribution in the transformer windings, it is necessary first to establish the distribution of currents of the positive I_1 , and the

winding voltage to $K(\dot{V}_\phi + \dot{I}_p Z')$ where K is a correction factor greater than one, based on the voltage drop caused by the asymmetrical load.

The voltage under asymmetrical-load conditions at the terminal of the tertiary winding, point III of the equivalent system of Figure 3, may be obtained by application of the methods of symmetrical components to the equivalent system. The positive-sequence voltage-drop component, starting from zero potential at point I in Figure 3, is $(-\dot{I}_1' Z' - \dot{I}_1 Z''')$ where I' is the component of the positive-sequence current in the path Z' . Similarly, the negative-sequence voltage drop at the same point is $(-\dot{I}_2' Z' - \dot{I}_2 Z''')$ where $\dot{I}_2'$ is the negative-sequence current in the path Z' .

It follows that, in Figure 3

$$\dot{V}_1 = \dot{V}_\phi - \dot{I}_1' Z' - \dot{I}_1 Z''' \quad (22)$$

and

$$\dot{V}_2 = -\dot{I}_2' Z' - \dot{I}_2 Z''' \quad (23)$$

where $\dot{V}_1$ and $\dot{V}_2$ are positive- and negative-sequence voltages, respectively, at point III.

The actual phase voltage will be

$$\dot{V}_a = \dot{V}_1 + \dot{V}_2 \quad (24)$$

$$\dot{V}_b = a^2 \dot{V}_1 + a \dot{V}_2 \quad (25)$$

$$\dot{V}_c = a \dot{V}_1 + a^2 \dot{V}_2 \quad (26)$$

and since

$$a^2 = -0.5 - j 0.866$$

and

$$a = -0.5 + j 0.866$$

equations 25 and 26 may be rewritten as

$$\dot{V}_b = -0.5(\dot{V}_1 + \dot{V}_2) + j 0.866(\dot{V}_1 - \dot{V}_2) \quad (27)$$

$$\dot{V}_c = -0.5(\dot{V}_1 + \dot{V}_2) - j 0.866(\dot{V}_1 - \dot{V}_2) \quad (28)$$

Figure 3. Equivalent star circuit of a three-winding transformer showing balanced load on the delta-connected secondary

The diagram shows a star configuration with three impedances Z', Z'', and Z''' connected to a common central point. The terminals are labeled I, II, and III. Impedance Z' is connected to terminal I, Z'' to terminal II, and Z''' to terminal III. A load Z_p is connected between terminal II and ground.

negative $\dot{I}_2$ sequences among the paths of the corresponding system. Such distribution is, of course, inversely proportional to the impedances of the parallel paths. Such current in each path must be added to the normal symmetrical current, I_p , of that path.

Then the current of the most-loaded phase of the primary winding will be

$$\dot{I}_a' = \dot{I}_p + \dot{I}_1 + \dot{I}_2 \quad (21)$$

In approximating the current components I_1 and I_2 of the asymmetrical load, only the normal no-load phase voltage, V_ϕ , at the terminals of the star-connected winding is considered. The corresponding phase voltage at the primary-winding terminals will be $\dot{V}_\phi + \dot{I}_p Z'$ where $\dot{I}_p Z'$ is the primary-winding voltage drop caused by the symmetrical load on the delta-connected secondary.

After the application of the asymmetrical load, the tertiary-winding voltage will be less than V_ϕ . It follows that conditions under which the currents I_1 and I_2 were first approximated will have been disturbed. In order that the terminal voltage V_ϕ be maintained constant with load, it is necessary to increase the primary-

From these equations the interphase voltages may be calculated to be

$$\dot{V}_{ab} = \dot{V}_a - \dot{V}_b = 1.5(\dot{V}_1 + \dot{V}_2) + j0.866(\dot{V}_1 - \dot{V}_2) \quad (29)$$

$$\dot{V}_{ca} = \dot{V}_c - \dot{V}_a = -1.5(\dot{V}_1 + \dot{V}_2) + j0.866(\dot{V}_1 - \dot{V}_2) \quad (30)$$

$$\dot{V}_{bc} = \dot{V}_b - \dot{V}_c = j1.732(\dot{V}_1 - \dot{V}_2) \quad (31)$$

In the foregoing discussion a factor K was presented to correct for the difference between load and no-load conditions of difference between terminal voltage at point III in Figure 3 and primary voltage

Table II. Relationship of Phase Load to Phase-Winding Load

Asymmetric Load in Per Cent of Total Load	Phase-Winding Load in Per Cent of Phase Load
80.....	100
70.....	91
67.....	82
55.....	75
50.....	70
46.....	63

at point I. The value of K may now be obtained as the arithmetic mean value of the calculated voltage ratios for the two loaded phases. If

$$K' = \frac{\sqrt{3} V_\phi}{V_{ab}} \quad (32)$$

and

$$K'' = \frac{\sqrt{3} V_\phi}{V_{ac}} \quad (33)$$

then

$$K = \frac{K' + K''}{2} \quad (34)$$

and

$$\dot{V}_a' = K(\dot{V}_\phi + \dot{I}_p' Z') \quad (35)$$

where $\dot{V}_a'$ is the primary voltage at point I in Figure 3.

Conclusion

The foregoing analysis of the loading of asymmetrical three-phase three-winding transformer banks has been verified by laboratory observations of current distribution and effective voltages under such conditions. A thorough practical investigation has confirmed fully the correctness of the conclusions arrived at mathematically.

It appears to be reasonable that equations established in this manner may be used in estimating the required capacity of the most-loaded phase of three-phase three-winding transformers subjected to such loading.

The results of calculations made for different combinations of symmetrical regional and asymmetrical traction loads are given in Table I.

In expressing the A -phase capacity in kilovolt-amperes, the transformer primary-winding power for this phase is represented by

$$P_a' = \dot{I}_a' V_a' \quad (36)$$

The predetermined transformer loads are

represented in Table I. As a first approximation, it is assumed that the phase load on the traction winding is the sum of the two path loads $P_{ab}/\sqrt{3} + P_{ac}/\sqrt{3}$ which fall on this phase, as shown in Figure 1. Actually this approximation will be higher than the measured winding load.

The symmetrical load of the delta-connected secondary is assumed to be the same in all three phases.

The results of the foregoing analysis disclose a characteristic feature of load distribution in three-phase three-winding transformers under the conditions of asymmetrical loading. As shown in Table I, the A -phase primary winding does not carry the sum of the secondary- and tertiary-winding loads of this phase as it would in the case of symmetrical loading. A part of the load of the most-loaded A phase will be carried by the other less-loaded phases.

The portion of the total phase load carried by the phase winding varies with the relationship between asymmetrical load and total load. The relationship for the most-loaded phase is shown in Table II.

According to Standard for Transformers of the Union of Soviet Socialist Republics, OCT 2,524, the size of the single-phase transformers of the three-phase bank will be determined by the relationships 100:67:100 and 100:67:67 corresponding to winding voltages of 110 kv, 35 kv, and 11 kv, respectively. These relationships are used for practical application to this type of loading.

Electrification of Large Open-Pit Copper Mines

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Synopsis: The transportation problem of a large strip mine involves the loading, hauling, and dumping of both ore and waste. These materials are loaded with large electric shovels operating on benches along the slope of a hill or pit. The ore is transported over main-line tracks to the reduction plant, while the waste is hauled to suitable dumps. All main-line tracks are permanent and are equipped with permanent overhead distribution systems (Figure 1). All bench and dump tracks are portable and are equipped with portable overhead distribution systems.

Sixty per cent of the world's copper is now obtained by open-pit mining of low-grade ore. Electrification of haulageways for open-pit mining is keeping pace with the expansion and is modernizing the transportation of huge tonnages. Huge capacities necessitating heavy cars and heavy grades demanding short-period overloads have been responsible for the selection of the electric locomotive for motive power. From the standpoint of locomotive capacity, rail size, dump-car capacity, and density of traffic, most open-pit electrifications compare in size with our large steam-road installations and hold an important place in the field of heavy traction (Figure 2).

In addition to describing the haulage problem of large open-pit copper mines, this paper discusses the design of permanent and portable distribution systems.

OPEN-pit mining, commonly called quarrying, is familiar to everybody and can scarcely be termed a new process, since materials for the many historic structures of Egypt, Rome, and China were obtained by "pit quarrying." However, open-pit mining, as applied to modern large tonnage operations, is a highly developed and highly mechanized process for recovering minerals from large ore bodies and is dependent on heavy haulage facilities, usually electrified.

Our domestic mine output of copper, estimated in excess of 1,000,000 tons for 1942 and representing 15 per cent increase over 1940, has been possible, chiefly because of the development of open-pit mining methods. Because of

high costs, underground mining is greatly limited to high-grade ores and to comparatively low tonnage. Deeper shafts and greater penetration increase the underground haulage costs, since access to the ore body must be made from the surface, and the shafts cannot be moved at will. Then, too, the depletion of easily available deposits of high-grade ore has influenced the expansion of open-pit mining. Therefore, either the mining of low-grade ores or the removal of large deposits involving considerable overburden and waste rock is almost exclusively a stripping operation. Strip mining has not only given the operator an economical plant but has put an end to an important waste in his plant—the waste of natural resources.

The Utah Copper Company is credited with originating the recovery of copper from low-grade ore on a large tonnage basis. Other companies, including Nevada Consolidated, Ray Consolidated, and Chino (Nevada Consolidated in New Mexico), furthered the development and commercialization of the process. South America and Africa are also large producers of copper from low-grade ores, the Katanga project in the Belgian Congo representing the most recent undertaking. At the present time 60 per cent of the world's copper is secured from mammoth strip operations in low-grade copper.

It has been only a short time since the bulk of our domestic copper was mined in Montana and Michigan, both states operating immense underground workings. Today the open pit mines in Arizona, Nevada, New Mexico, and Utah are producing large quantities of copper from low-grade ores, and, as a consequence, Montana and Michigan are third and sixth, respectively, on the list of copper-producing states. Some de-

tailed data for 1941 may be found in Table I.

It is interesting to note from Table I that Arizona and Utah produced 62 per cent of the domestic copper in 1941. Statistics also show that these states produced 18 per cent of the world copper in 1939, the last year for which accurate figures were available. Perhaps a description of one of the most recent open-pit undertakings will acquaint you with modern large-scale stripping operation, and also with the importance of adequate transportation facilities for handling the thousands of tons of ore and waste. This operation is the Morenci mine of the Phelps Dodge Corporation in Arizona.

Typical Example of Open-Pit Mining

Early mining operations at Morenci were underground. Evidence of this early mining can be seen in several locations in the new pit, where stripping has broken through the old workings. Only the high-grade deposits attracted the first miner. Operations were restricted to the secondary enriched areas and to replacement deposits occurring in sedimentary rocks. The copper content of these ores was adequate to warrant the cost of mining, transporting, milling, and smelting. Following the exhaustion of these ores, mining operations were transferred to the monzonite porphyry, where rich ore was again found in fissures also as disseminations in the porphyry. Later, mining was extended to the lower-grade disseminated ores where operation by the block-caving method continued for many years.

All of this early mining contributed to the development of the new Morenci pit. Commercial mining uncovered the large deposits of low-grade porphyry ore. Extensive exploration work with churn drills, diamond drills, and continued underground mining fixed the pit limits and determined the size and quality of the huge ore body.

The low-grade ore of the Morenci pit consists chiefly of chalcocite disseminated in monzonite porphyry. Chalcocite, a sulphide ore, occurs in many of the western open-pit copper mines, such as the Bingham mine of the Utah Copper Company, the Phelps Dodge Corporation Ajo pit, and the open pits of the Nevada Consolidated Copper Corporation at Santa Rita, N. Mex., and McGill, Nevada. Rarely does the copper content of these large open-pit mines average more than one per cent. At Morenci, the ore averages 1.06 per cent copper.

Table I. Copper-Producing States

State	Tons
Arizona.....	326,000
Utah.....	267,000
Montana.....	128,000
Nevada.....	79,000
New Mexico.....	73,000
Michigan.....	46,000
Other states.....	38,000

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Economy dictates the amount of waste that can be removed in any stripping area (Figure 3). The cost of loading, hauling, and dumping must be maintained within a definite figure. Too much waste removal, long hauls, and distant waste dumps increase mining costs. For all stripping operations the amount of waste that can be removed economically bears a definite relationship to the amount of ore recovered. For coal stripping, the miner's rule of thumb is one foot of overburden for one inch of coal. In low-grade high-tonnage copper-stripping operations the ratio is one ton of waste for one ton of ore. Therefore, the hauling of ore is one half of the problem, and the hauling of wastes is the other half.

At Morenci the waste includes an overburden, or capping, which has a maximum thickness of 500 feet and an average thickness of 216 feet above the ore body. Preliminary stripping required the removal of 50,000,000 tons of material, mostly waste, in order to assure the initial removal of 25,000 tons of ore daily. All material not used for truck highways was hauled to dumps or to the railroad right of way for fills. The preliminary digging in was accomplished with 18 large trucks capable of handling 22½ yards of material. Many miles of excellent roadway were constructed for truck haulage, since the loaded truck weight was 65 tons, and grades were as high as ten per cent.

The removal of ore at Morenci is accomplished by the establishment of a series of benches, the number depending on production requirements (Figure 4). Since each bench represents a separate or independent mining operation, this bench method of open-pit mining is usually the most economical. The benches are equivalent to a stairway, each tread representing the floor where the shovels operate to load dump cars, each riser representing the working face where the ore is broken away. The height of the bench is determined by the shovel equipment, limitations to drilling, and the nature of the material. In this case the height of each bench is 50 feet, and its width, being determined by the requirements for shovel operation and haulage facilities, is 100 feet.

The Haulage Problem

Following the establishment of benches, the ore and waste rock are broken away from the face by blasting, the length of the blasted section often extending a distance of 1,000 feet (Figure 5). For load-

ing purposes, secondary blasting is usually necessary for further fragmentation of the larger rocks. Additional blasting is also necessary for removing the toe where the face and floor intersect. Removal of the toe provides a vertical bank and reduces overshooting and undershooting, thus permitting the burden carried by each drill hole to be estimated more accurately. The preparation of ore, therefore, becomes an important factor in the haulage problem. The track and overhead distribution system must be planned either for quick removal or for resisting a certain amount of flying rock fragments.

The loading of ore and waste at Morenci is accomplished with a full-revolving electric shovel equipped with a 4½-yard dipper (Figure 6). A bulldozer aids in leveling the bench and scraping stray rock towards the reach of the shovel. It also serves to move the spillage from the area of the track. The ore is loaded in trains of ten 40-ton side dump cars, each equipped with axleless trucks and roller bearings, while the waste is loaded in trains of nine 30-ton cars of equivalent design (Figure 7). Sufficient cars or trains are available at the shovels to maintain a shovel efficiency of 87 per cent. Clearance, then, is another important factor in the planning of the open-pit mining operation. There must be sufficient clearance and overhead to permit unrestricted operation of the shovel, and there must be sufficient track clearance to permit the unrestricted movement of the bulldozer (Figures 8 and 9).

Naturally, the tracks on the benches and waste dumps cannot be aligned and surfaced as well as main-line tracks. Settlement on the fills and uneven floor on the benches makes surfacing difficult. The constant moving of tracks on both the waste dumps and the benches prevents good track alignment. As a result locomotives and rolling stock are designed to meet this problem, and the locomotive, particularly, must successfully withstand short-time overloads when negotiating uneven track and severe grades.

As explained in this description of the Morenci operations, open-pit mining consists of the removal of ore and waste from a series of shelves or benches, one above the other, and each operates as a separate mine. The operation may be either a pit operation or the tearing down of a mountain. Benches are employed in either case. The actual mining consists of blasting down ore, loading in suitable dump cars, and hauling ore to the mill or reduction plant. The haul-

age way includes permanent tracks and portable tracks. The permanent tracks are located between the mine and mill and also include the storage yards. The portable tracks are located on the benches and on the waste dumps. Switchbacks that are necessary for ascending from one bench to the next are usually permanent tracks. The overhead trolley system must correspond to the track construction. It must be either permanent or portable.

Progress of Electrification at Large Western Mines

The four large open-pit copper mines located in the West and Southwest, that are either wholly or partially electrified, are moving a daily tonnage of approximately 300,000 tons of ore and waste. This material represents more than 6,000 carloads and is handled with 100 electric locomotives over 200 miles of track. The locomotives at the Utah Copper Company, and also the two Nevada Consolidated Copper Corporation's operations at McGill, Nev., and Santa Rita, N.Mex., are 85-ton machines, whereas the 16 locomotives at Morenci are 125-ton machines. All mines operate with an overhead trolley voltage of 750 volts direct current. The combined substation capacity of the four electrifications for traction purposes is 15,000 kw, and the combined locomotive capacity is 100,000 horsepower.

Overhead Distribution System

The overhead distribution system performs a very important part in the operation of the open-pit mine, and is not merely "a place to park the pantograph." The steam locomotive requires its coaling equipment, its water plant, and its cinder pits. The diesel-electric locomotive requires its fuel storage and its fuel distribution system. The electric locomotive requires its substations and its overhead distribution system. Therefore, the electric distribution system becomes the auxiliary equipment for the electric locomotive. The distribution system is the fueling system.

The specifications for the two types of overhead systems, permanent and portable, are quite different. The permanent track is operated with the usual type of pantograph mounted on the roof of the cab, while the portable track is operated with a side-arm collector. The trolley wire is over the track center on permanent right of way and offset to the



Figure 1. Over 6,000 cars of ore and waste are hauled daily by electric locomotive in the large open-pit copper mines of the United States

Figure 2. The electrification of open-pit mines has become an important factor in the field of heavy traction

Figure 3. During preliminary stripping at Morenci, waste material was used for roadways and railroad fills

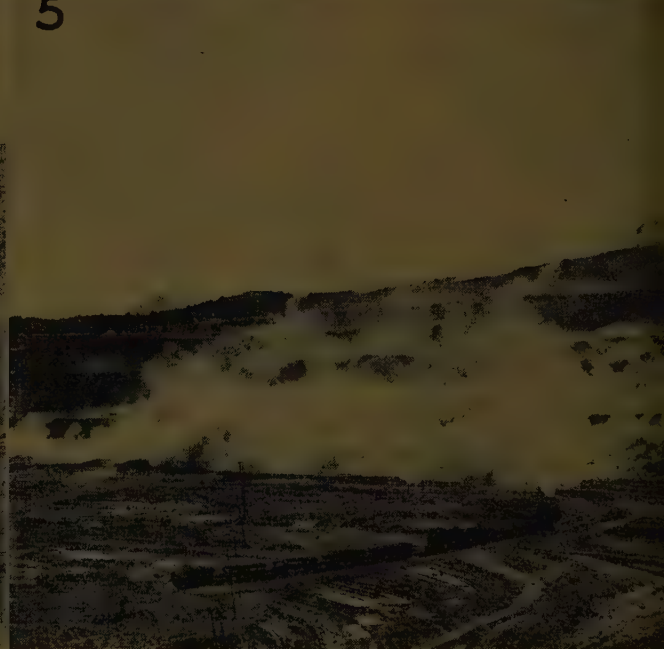
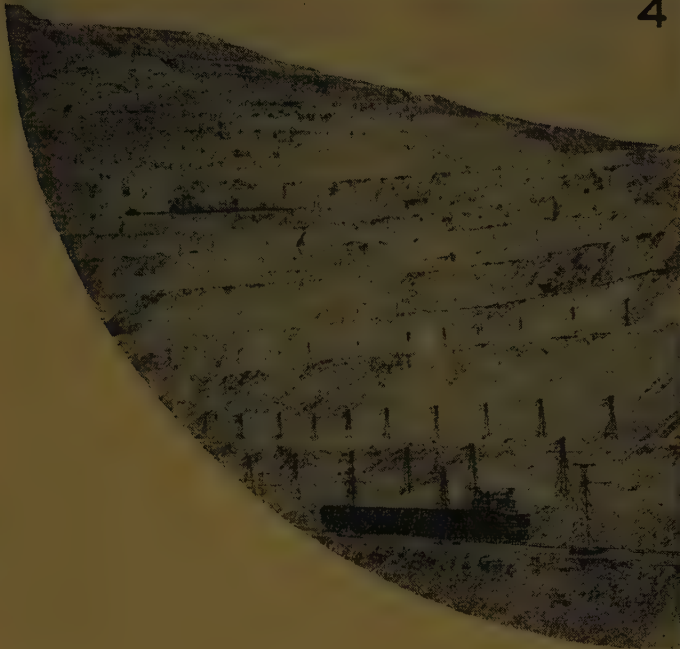


Figure 4. Each bench represents a separate or independent mining operation

Figure 5. Ore is broken away from benches by blasting, the length of the blasted section often extending a distance of 1,000 feet

Figure 6. Full-revolving electric shovels with $4\frac{1}{2}$ -yard dippers loaded $22\frac{1}{2}$ -yard dump trucks during preliminary digging in at Morenci



side of the track along the portable sections. We will describe the portable overhead first.

Portable Overhead System

The portable overhead system is used at any location where it is necessary to move the track at frequent intervals. The tracks on the benches are moved towards the face as mining progresses, and the tracks along the waste dump are moved towards the shoulder of the dump as the dump is filled out. On the bench tracks, head clearance must be maintained for loading, since the dipper of the shovel reaches over the center line of track. Crane equipment is frequently operated over both the bench tracks and the dump tracks; therefore, overhead clearance is necessary over these tracks. The usual offset of trolley wire from the center of track is from 10 to 16 feet. Of course, the offset on the benches is on the side opposite the shovel.

Portable structures are usually steel, either constructed of fabricated shapes or pipe. Owing to the constant handling, a wooden structure does not have sufficient life and is easily splintered. The pipe structure is the simplest and requires less maintenance.

One of the simplest pipe structures is used on the Utah operations at Bingham. This structure consists of a five-inch pipe embedded in a concrete footing and supporting, at its top, a bracket arm which in turn, supports the trolley wire. The concrete footing is elongated, as illustrated in Figure 10 and is equivalent to a sled or stoneboat in contour. It is equipped with a large eye bolt for pulling and can also be shoved into position with a bulldozer. This type of portable structure is easily transported from one bench to another and can be moved easily as mining progresses. A similar structure is used by the Canadian Johns-Manville Company for the mining of asbestos at their open-pit operation at Asbestos, Que., Can. This structure, however, is fabricated of lighter pipe. The illustration in Figure 11 shows how the footing is spread and mounted on stringers. This structure does not require a bracket arm for supporting the trolley wire; the gooseneck upper end of the main pipe performs this function. This type of structure has no flexibility from the standpoint of trolley-wire alignment. The entire structure must be moved along the ground to obtain this feature. Because of its lightness it is easy to move, but the curved arm does not have ample reach for some types of collectors.

One of the most recent and useful types of portable supporting structures is used at the new Katanga copper mine in the Belgian Congo. This structure, Figure 12, employs a five-inch tubular pole, a base, a bracket arm, and a special pole collar. The pole is supported in a cast-iron socket. The pole band has a large vertical hole or socket into which a pin on the bracket is inserted. A pad on the lower end of the knee brace lays against the pole for additional support. Since the center of rotation of the bracket arm about the pin does not coincide with the center of rotation of the pad, very little swing can be obtained by the bracket arm. However, there is sufficient clearance between the pin and the socket in the pole band to permit some movement, thus providing relief in the bracket arm in case the trolley-wire tension becomes unequal on either side of the pole.

To install the structure, the cast-iron socket is first placed in position. The socket may either be attached to a sled, in which case it is integral with the sled, or it may be spiked to extended cross ties. Next, the pole is inserted and keyed in the socket. This is usually a crane job with the locomotive crane pulling a flat car on which the structure material is loaded. The bracket arm is then lifted and its pin dropped into the socket in the pole band, the pole band having first been attached to the pole at the proper height before the pole is set in the base. The trolley wire is then strung and tensioned.

When the portable structures are hauled to new locations, the assembly procedure is sometimes altered. Another pole band is attached to the pole at a location about five feet above the ground. After the five-inch pipe has been dropped and keyed into the base, the pole bracket is then attached to this second pole band nearer the ground. At this height the lineman strings the trolley wire. After the wire is in place the brackets are lifted, one at a time, and placed on the pole bands at the top of the poles and at the proper height. Of course, the trolley wire is slack when the bracket arms are lifted; otherwise, the wire would tend to tip the poles. After the bracket arms are in place at the top of the pole, the trolley wire is tensioned and clamped.

A special type of trolley clamp is used for portable structures (Figure 13). This clamp provides not only the usual jaws for clamping the grooved trolley wire but also an opening above the jaws where the wire can be supported but not

clamped. When the overhead system is in operation, the trolley wire is clamped in the lower part of the jaws and cannot be pulled through the jaws, but, while the structures are being moved, the trolley wire is held loosely in the opening above the clamps. Thus, the trolley wire is free to slide longitudinally when the poles are moved to a new position. After the structures are in place the trolley wire is tensioned by pulling the free end. The wire is then dropped into the lower portion of the clamps, and the jaws are tightened on the wire. The reverse of this operation is necessary when it is time to move the poles to another location. The jaws of the trolley-wire clamp are first loosened, and the trolley wire is pushed up and into the upper recess. The jaws are then tightened again in order to prevent the wire from falling out of the clamp.

The trolley clamp is usually insulated with a composition hanger with a malleable-iron protecting shell which withstands the flying rock fragments.

The fabricated structure illustrated in Figure 15 supports both the 750-volt d-c trolley wire and the 5,500-volt a-c electric-shovel circuit at both Utah Copper and the Santa Rita operation of the Nevada Consolidated Copper Corporation. In some instances the d-c feeder is also carried on the portable structures; however, the method of feeding the bench tracks does not require longitudinal feeder.

The installation of over 2,000 portable structures at the Bingham mine of the Utah Copper Company has demonstrated the usefulness of this type of haulage. Some of the original locomotives at Bingham were equipped with storage batteries to be used for the supply of energy in sections of waste dumps and other locations. It was thought that portable poles could not be used. Today all operations are supplied with an overhead trolley wire, batteries having disappeared from the scene. With adequate overhead clearance and properly designed structures there is no interference with loading and unloading, and the portable system can be moved quickly and cheaply. With a force consisting of a crane, three pit crews for the track, and two electricians, Utah moves 3,000 feet of track and portable overhead in five hours.

Permanent Overhead System

Two types of overhead are used on permanent track. Both types must provide clearances for pantograph operation.



Figure 7. 125-ton 750-volt locomotive operating at Morenci

this type of catenary, but it is designed also for good current collection and for other characteristics. The catenary spans are spaced 120 feet on tangent, and on curves it is spaced 80, 60, and 50 feet, depending on the degree of curvature. Most of the curves, however, use 80-foot spans. With reference to Figure 16, it may be observed that three main-line haulage

Direct suspension, usually requiring supplementary feeder, is selected for slow speeds and full load currents below 1,000 amperes. Catenary overhead is selected to reduce initial cost and the number of supporting structures and to provide a better means for the supplying and collection of high currents. The choice of the distribution system, therefore, is based on the limitations and specifications of each electrification. As examples, the recent Katanga installation in the Belgian Congo with 66-ton locomotives is constructed with direct suspension using a single 4/0 contact wire on permanent or main-line sections, whereas the Morenci mine of Phelps Dodge Corporation with 125-ton locomotives is constructed with a compound catenary system consisting of a 350,000-centimeter hard-drawn copper main messenger cable, a 3/0 19-wire hard-drawn copper intermediate messenger, and 4/0-grooved hard-drawn copper contact wire. As a general rule, yards are constructed with light catenary in order to reduce the number of supporting structures and provide greater visibility, as well as man clearance around cars. The Utah Copper Company and the Nevada Consolidated Copper Corporation have installed many miles of light catenary along permanent tracks including storage yards, crusher yards, and main haulage out of the mines. The light catenary consists of a 7/16 Siemens-Martin messenger cable supporting a 4/0-grooved contact wire with flexible hangers.

Simplified Catenary Span

With reference to the Morenci mine of Phelps Dodge Corporation, the type of haulage made possible the selection of a modified type of catenary which, heretofore, has not been applied to mine electrification. Ease of construction and maintenance are the chief advantages of



Figure 8. Unrestricted overhead clearance must be provided for the operation of the electric



Figure 9. Side-arm collection provides overhead clearance for movement of locomotive



Figure 10. Portable structures consisting of tubular poles supported on concrete stone are used on bench lines at Utah Copper Company

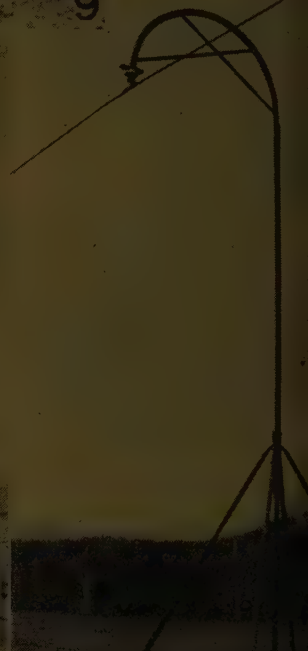


Figure 11. Portable structures consisting of tubular poles supported on concrete stone are used on bench lines at Johns-Manville Company, Ltd. portable structure

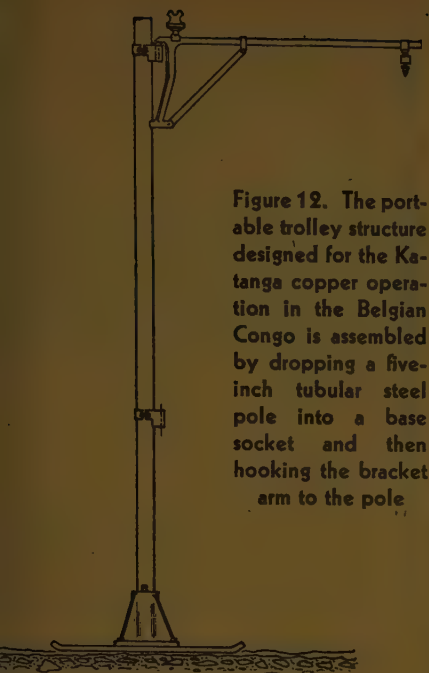


Figure 12. The portable trolley structure designed for the Katanga copper operation in the Belgian Congo is assembled by dropping a five-inch tubular steel pole into a base socket and then hooking the bracket arm to the pole.



Figure 13. When a portable structure is to be moved, the grooved trolley wire is removed from the jaws of the clamp and inserted in an upper groove where the wire will slide freely.

are used on the 120-foot spans. The end hangers are located 20 feet from each point of support, while the third hanger is located midway on the span. This main-messenger-hanger spacing divides the intermediate cable spans into 40-foot lengths. The trolley wire is supported by three clips attached at equal intervals to the intermediate cable. The center clip is two inches in length, whereas the two end clips are three inches in length. With this type of construction good contact between fittings and cable is obtained for the flow of electric energy from the messengers to the contact wire. As explained in the preceding description, a minimum number of hangers is required. The 120-foot span requires only two lengths of main-line hangers and two clips. The 80-, 60-, and 50-foot spans require additional lengths of main-line hangers, but the same two-clip construction is used throughout the entire line. With this type of catenary span the total number of main-messenger hangers will not exceed 9 for the spans indicated, whereas the total number of hangers for the conventional span might easily exceed 50 when the special length spans are considered.

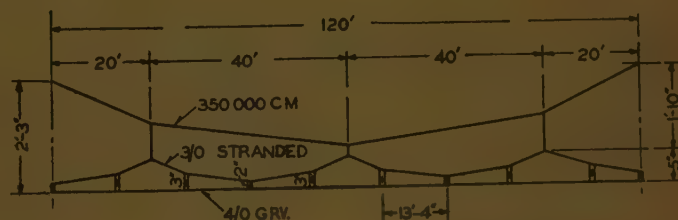


Figure 14. Portable structures mounted on truck wheels are moved over short sections of rail on dump tracks of International Nickel Company.



Figure 15. Fabricated structures support the 750-volt d-c trolley wire and the a-c shovel circuit at Utah Copper Company.

Figure 16. This catenary span reduces the number of main-catenary hangers to a minimum.



Although tangent pole spacing on the Morenci electrification is only 120 feet, and the nominal pole spacing on light catenary at the mines of the Utah Copper Company and the two operations of the Nevada Consolidated Copper Corporation is 150 feet, the spacing of catenary spans is not limited to these dimensions, except by economy and physical limitations (Figure 17). These operations, from the standpoint of rolling stock, locomotives, and rail size (131 pounds at Morenci) are comparable to many large steam-road electrifications, and with sufficient main-line track would undoubtedly be built with structures spaced at 300-foot intervals.

A Bit of History

The Utah Copper Company electrified the crusher yards at both the Magna and Arthur plants in 1925 (Figure 18). Two 80-ton locomotives, formerly used by the Manufacturers' Railroad of St. Louis, were installed in these yards. The total trackage was slightly over eight miles. During 1936 a large part of this crusher-yard electrification was torn down, and one of the mills was partially dismantled. During the following year, however, because of improved market conditions, the mill was again placed in operation and this nine-year-old catenary system was rebuilt with scarcely any loss in line material. Naturally, the electrical department was adept in taking down and rebuilding overhead systems, since this is daily procedure for the open-pit mine electrification. The original system is in operation today.

Supporting Structures for Permanent Track

Supporting poles are either wood or steel. At the Utah Copper Company mines, wood poles are used on permanent haulage, with the exception of the yards. Wood poles have been used extensively at the Canadian Johns-Manville mines at Asbestos, Que. Long outside haulage tracks of the International Nickel Company, near Sudbury, Ont., are equipped with wood poles for supporting light catenary overhead. The



Figure 17. Compound catenary on permanent track at Morenci

use of wood depends entirely on the permanency of the electrification and the cost of the poles; however, at the Katanga mines in the Belgian Congo, wood is prohibited because of the destruction caused by ants. On tangent, the wood pole spaced 150 feet and supporting light catenary which does not exceed 1½ pounds per foot can be used without guys, whereas longer spacings with heavier mechanical loads require guying.

Some of the yards at Utah are built with fabricated steel structures supporting cross spans or cross catenary, whereas the large storage yard of the Nevada Consolidated at Santa Rita, N. Mex., is built with wide-flange beams. The entire McGill electrification of the Nevada Consolidated is also built with wide-flange beams (Figures 19 and 20). Tubular steel poles, consisting of five-inch standard pipe, are used for permanent track on the Belgian Congo installation. These tubes are embedded in concrete. Steel poles, whether fabricated structures or shapes, are mounted on footings with anchor bolts at Utah and Santa Rita

Figure 18. Crusher-yard catenary at Utah Copper Company was removed from this area after nine years of operation and later reinstalled with practically no loss of equipment



(Figure 21). At McGill, all steel poles are embedded, the footings having first been cast with a center well into which the pole is placed and subsequently grouted. The Utah fabricated poles are galvanized.

Substations

The most modern substation equipment is to be found at open-pit electrifications. At Santa Rita, the d-c substation includes two 1,000-kw rectifiers and an automatic switchboard. Normally, one rectifier operates on loads of 1,500 amperes or less. When the load exceeds 1,500 amperes for a period of two minutes, the second rectifier cuts in and will remain on the line until the load drops below 1,500 amperes for a 50-minute period. The railway system is divided into four sections. Each section is fed separately and is protected with 1,500-ampere breakers. At Morenci, four 1,000-kw rectifiers supply the traction energy. The Katanga operation has two rectifier substations, one on each end of the pit. Utah has three substations with a total capacity of 9,000 kw. These substations are located at the various load centers throughout the mine.

The ratios of substation capacity to connected load for some of the large strip operations are:

Utah.....	19 per cent
Morenci.....	22 per cent
Santa Rita.....	24 per cent

From these low ratios it can be seen that the various operations making up the haulage requirements are intermittent, and, although a locomotive is in service 24 hours each day, it may actually operate only 20 per cent of the time. As an example, the loading operation for a train may require 60 minutes, but the total time required by the locomotive for inching the cars in this 60-



Figure 19. Light catenary installed on wide-flange portal structures is used for permanent track at Santa Rita

minute interval can be as low as three minutes. Consequently, the locomotive is in operation just five per cent of the loading time. Naturally, the haul from the mine to the crusher increases the overall ratio, but in the case of the Utah Copper Company at Bingham, Utah, the ratio is quite low, indicating low cost of conversion equipment.

D-C Feeder

Since each bench track and each dump track may be considered as a separate electrification, it may be concluded that a bench track that is served by only one locomotive cannot be equipped with feeder that has been calculated by using the ratio of installed substation capacity to the installed locomotive capacity. The single locomotive operates alone. Its load cannot be averaged with the



Figure 20. Yard catenary at Santa Rita. Columns are bolted to footings



Figure 21. At McGill, Nev., wide-flange columns are embedded in concrete footings cast with center well

loads of many other locomotives; therefore, the ratio used in calculating d-c feeder is much higher than the over-all mine ratio. Since the locomotives on a bench track or waste dump operate at very slow speeds, usually about three miles per hour, the current collected with the pantograph is not apt to reach anything like full load current. In fact, the current is usually one-half to one-third full load current. As a consequence, the ratio considered, when a feeder is designed for the mine, is usually 33 per cent, or as high as 50 per cent, if it is possible to increase current by increasing speeds. The usual ratio for underground coal operations for determining d-c feeder for traction purposes varies from 33 per cent to 45 per cent.

In general, comparatively little d-c feeder is necessary for the loads en-

countered. Very little longitudinal feeder is installed, since the many paralleling tracks on benches and yards provide the necessary copper. However, transverse feeding is quite common and is necessary to cross connect the trolley wires on a group of paralleling tracks. Section insulation is inserted at advantageous points where it is necessary, either to break the feeding or to protect the system against interruption of service because of some fault on one of the benches or on the waste dump. It has been the practice at the Utah Copper Company mine to feed a group of six locomotives on three benches from two sources of power. With this arrangement an interruption is localized and does not affect the entire operation. Yards, as a rule, are fed as one unit—insulation is not placed between tracks for segregation.

Bonds

Track bonds fall under two general types. For portable track a removable bond is used, and for permanent track a permanently attached bond is used. The removable bond is either the wedge type, which is a low-resistance copper-terminal bond that extends around the splice bar and is attached by driving a wedge into the web of the rail, or a temporary bond which also surrounds the

splice bar and attaches to the base of the rail with large set screws.

The permanent track is bonded with short welded bonds, usually electric-welded, since the d-c circuit may be utilized both for the initial installation and for maintenance. A 4/0 bond is sufficient for rails in the 90-100-pound class, while the heavy main-line rail, usually 131 pounds, is connected with two 4/0 bonds. Cross bonds are placed at 500- to 1,000-foot intervals, depending on the type of track. Closer spacing is used on the temporary tracks (Figure 22).

Organization

The operators of large open-pit electrifications are to be commended on their ability to construct low-cost jobs. Fundamentally, the mine operator is not a man to split hairs with respect to the cost of equipment. Enormous tonnage and the necessity for low-cost haulage will prompt him to install adequate and reliable equipment and equipment that has been proved. As a consequence, one of the usual high items of expense is missing—engineering cost. The average engineering force for a large mine electrification rarely exceeds three, and these men are the regular electrical force of the mine. Outside consultation is secured from the manufacturer of equipment and from



Figure 22 (left). Gas-weld 4/0 bonds are applied to tracks at Santa Rita



Figure 23 (right). Construction and maintenance car at Morenci

other mine operators. The mine operator does not insist on numerous gadgets and changes in design, but insists on dependable equipment as well as simple equipment. The job of moving thousands of tons of material daily is dependent on a minimum of breakdowns and, since mining has become a production-line process, transportation must function satisfactorily. Simplicity, a synonym for low cost, is the first rule of mining.

The nucleus of the construction forces is gathered from the mine. The foremen are usually acquainted with the designs and procedure before actual building starts. Therefore, the builders take an active interest in the equipment and in the construction and become trained maintenance men before actual operation is initiated. This procedure ultimately reduces maintenance costs and, to a great extent, the necessity for servicing (Figure 23).

Costs

When it is realized, that at one large strip mine the cost of water for steam locomotives paid the power bill after electrification, few additional data are necessary to convince the mine operator that electrification is economical. At McGill, Nev., the cost of haulage was reduced, by the substitution of electric energy for steam, from 10 cents to 3.4 cents per ton. At Morenci the cost of electric haulage is only two cents per ton, or slightly less than one cent per ton-mile, a figure that compares with the average cost per ton-mile on class 1 railroads.

Advantages of Electrification

A specific example of the advantages of open-pit electrification is found at Bingham. Here the number of loaded cars in an ore train has increased 25 per cent, and speed has increased 25 per cent. Therefore, fewer locomotives are necessary per shovel.

In general, with electric operation, there is less track wear due to the articulated locomotive, and there are fewer car derailments. With electrification there is no burning of wood cross-ties, an expense which was once tremendous in large mines. The electric locomotive does not require the transportation of fuel and water, an operation which added a large amount to the cost of haulage. Enginemen have greater vision while operating in and out of the pits,

An Instrument for the Measurement of Large Alternating Currents

WALTHER RICHTER

FELLOW AIEE

Synopsis: An arrangement of the measurement and oscillographic recording of large alternating currents, consisting of a special air-core transformer and an amplifier, is described. The air-core transformer is wound on a flexible core of small cross section, permitting its easy linkage with the current to be measured without disturbing the circuit. The underlying theory of the air-core transformer is discussed, and the modifications necessary to make it suitable for measurement purposes are described.

THE measurement of large alternating currents, as required on the low-voltage side of resistance and flash welding transformers for instance, is an important problem, and many suggestions for satisfactory solutions have been made.¹

The ordinary current transformer, such as used in almost all a-c measuring circuits, operates on the principle that in any iron-core transformer working with a low magnetic flux density in the iron core the total excitation resulting from the two windings is nearly zero. This means that the ampere turns produced by the meter winding equal the ampere turns or the amperes, in the case of a single conductor, of the current to be measured. Since the current density in the meter winding cannot, as a rule, be made higher than the current density in the primary conductor, which, it can be assumed, has been chosen as high as per-

missible with regard to the heating of the primary conductor, the copper cross section of the meter winding must at least equal the cross section of the primary conductor; the total space taken by the meter winding will be increased further by the insulation of this winding. In addition to this, the two windings must be made to link with a closed iron core. In low-voltage welding circuits every effort has been made usually to reduce the spread between the leads, or the "loop," to a minimum, and the insertion of a current transformer, which, for the reasons previously mentioned, necessarily will be bulky, is usually out of the question.

Suggestions have been made that a part of the welding circuit be used as a shunt for a meter. This scheme runs into difficulty from skin effects, especially for distorted wave shapes such as those that occur in flash-welding currents, and requires very careful placement of the leads to avoid inductive pickup. The calibration also presents some problems.

Air-core transformers have been used for the measurement of large alternating currents,² and this paper deals with a special arrangement of this type of transformer. Any air-core transformer is unsuitable for the measurement of currents without certain modifications, as will be evident from the following. Its operation is based on the fact that in the vicinity of a conductor carrying alternating current there will be an alternating magnetic field, the intensity of which will be proportional to the current if no iron masses are close by. If a coil is placed in this field, a voltage will be induced in it, and this voltage may be used as an indication of the current. Since the induced voltage equals $M \times di/dt$, where M is the mutual inductance between the

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WALTHER RICHTER, now electrical engineer in the engineering development department of Allis-Chalmers Manufacturing Company, Milwaukee, Wis., was an independent consulting engineer at the time this paper was written.

The author expresses thanks for the suggestions of W. E. Crawford, E. J. Limpel, and A. Paalu of the A. O. Smith Corporation, the laboratory in which the device described in this paper was developed.

and the elimination of smoke helps pit operation, since good visibility is a big factor in the operation of a mine.

In conclusion, the electric locomotive is reliable. At the Bingham mine of the Utah Copper Company there are 65 locomotives, and there is rarely a time when more than two are in the shop.

The electric locomotive is not affected by bad water, and its breathing apparatus is not susceptible to change in altitude. It consumes but one grade of fuel, and that is the best grade. The electric locomotive has proved a successful factor in the operation of large open-pit copper mines.

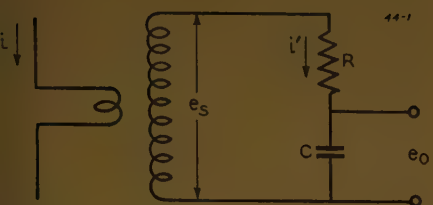


Figure 1. Circuit for electrical integration of an alternating voltage

primary conductor and the pickup coil, it is evident that the instantaneous values of this voltage are not proportional to the instantaneous values of the current, but rather to the instantaneous values of the rate of change of current. When a sinusoidal current of known frequency is dealt with, the voltage induced in the pickup coil will, of course, again be a sine wave, 90 degrees displaced against the current wave. In this case, the rms value of this voltage may be used safely as an indication of the current, as long as no phase relations are deduced from it. But let us assume now that the frequency of the current doubles, while its amplitude and rms. value remain constant. Since di/dt doubles, the voltage in the pickup coil will also double. From this it is at once apparent that the air-core transformer fails to indicate the current by the induced voltage if the current has a distorted wave shape, that is, has harmonics. This is especially true in flash welding, but even in plain resistance welding the current may change in wave shape if electronic tubes are used to control the firing point in the cycle.

A second difficulty lies in the fact that the placement of the pickup coil determines the value of M and with it the magnitude of the induced voltage. This difficulty has been overcome to a large degree, however, by most of the workers in this field, by properly shaping and placing the pickup coil, and their method of approach has been utilized also in the present arrangement.

After the two essential problems of the air-core transformer have been stated thus, the methods of solving them will be discussed.

The voltage $e_s = M \times di/dt$, induced in the pickup coil, is a result of a differentiation of current, as the formula indicates. If the reversed operation, that is, an integration, is performed on it, the resulting wave will be a replica of the original current wave. This integration can be carried out electrically by the simple circuit shown in Figure 1. Let the periodic voltage e_s be applied to the series combination of R and C , and let the value of C be such, that its reactance is small compared with the value of R ,

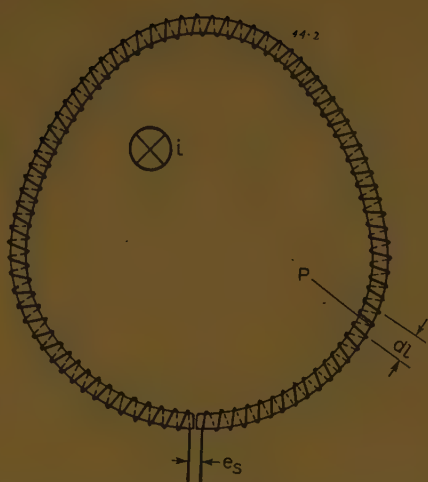


Figure 2. Linkage of toroid with current to be measured

even at the fundamental frequency of e_s . Under this condition the current through R and C will be determined essentially by the value of R only; that is, we can write without serious error

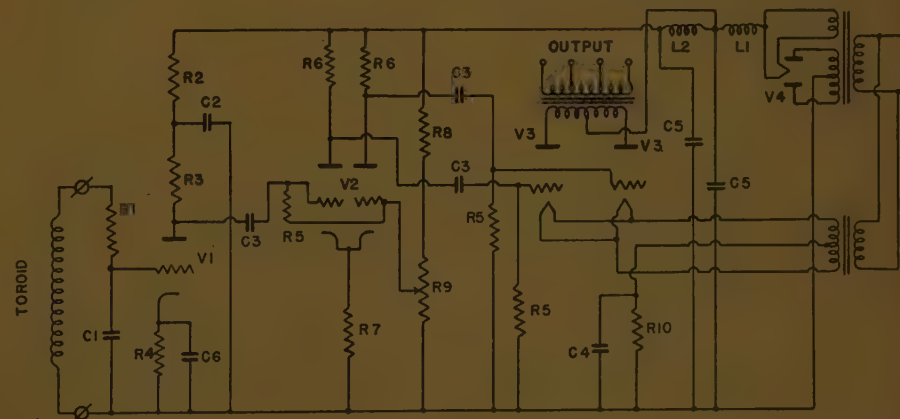
$$i' = \frac{e_s}{R} = \frac{M}{R} \times \frac{di}{dt} \quad (1)$$

The voltage across the capacitor will be

$$e_0 = \frac{Q}{C} = \frac{\int i' dt}{C} = \frac{M}{R \times C} \times \int di = i \times \frac{M}{R \times C} \quad (2)$$

Figure 3. Amplifier and integrating circuit

V1—6F5 tube	R2 — 10,000-ohm resistor
V2—6N7 tube	
V3—2A3 tube	R3 — 250,000-ohm resistor
V4—80 tube	
C1—0.5-microfarad capacitor	R4 — 5,000-ohm resistor
C2—24-microfarad capacitor	R6 — 50,000-ohm resistor
C3—1-microfarad capacitor	R7 — 20,000-ohm resistor
C4—100-microfarad capacitor	R8 — 10,000-ohm resistor
C5—16-microfarad capacitor	R9 — 10,000-ohm potential divider
C6—50-microfarad capacitor	R10— 375-ohm resistor
R1 —150,000-ohm resistor	



It must, of course, be realized that for this relation to be strictly true, the capacitor would have to be infinitely large, so that all the voltage e_s appears across R . However, the larger C , the smaller the output voltage e_0 , and the higher the amplification will have to be, before use can be made of this voltage. In the present instrument $R=100,000$ ohms, $C=0.5$ microfarad, which makes the reactance of the capacitor at 60 cycles per second roughly five per cent of the value of the resistance; this seemed to be a fair compromise between accuracy and amplifier requirements.

To make the voltage induced in the pickup coil as nearly independent as possible of the position of the coil, it must have the proper shape and must be placed according to certain fundamentals. The basic law of electromagnetism states that the line integral of the tangential component of the magnetic-field intensity around any closed path equals 0.4π times the exciting ampere turns linking with the path, that is

$$\oint H_t dl = 0.4 \pi i \quad (3)$$

where H_t is the component tangential to the path around which the integration is to be performed.

Suppose we surround the current with a toroidal* coil, wound on a flexible core, a length of heavy-walled rubber tubing, for instance. The winding is distributed uniformly over the whole length. Let n' be the number of turns per centimeter, so that the total number of turns N is equal to $n' \times l$, where l is the length of

*The terms toroid and toroidal are used here and in the following for the sake of brevity, although the coil described here does not have to be a true toroid. A toroid is defined as the surface generated by the rotation of a plane closed curve around an axis lying in its plane. In this paper we mean a coil wound on a surface generated by moving a plane closed curve along a closed path in such a manner that its plane is always perpendicular to the direction of the motion, which is a cumbersome way of saying: Take a heavy-walled rubber tube, make a "doughnut" out of it, and place a uniformly distributed winding on it; then deform the "doughnut" any way you like (as long as you do not squeeze its cross section).

the tubing. The cross section of the core, that is, of the tubing, is held small enough so that the average magnetic density over the whole cross section can be considered, without serious error, equal to the magnetic density existing along the axis of the toroid at any given point P . Since the plane of each individual turn is essentially at right angles to the axis, a voltage caused by a changing magnetic field will be induced only by the component tangential to the axis. If A is the area of one coil turn, which in most practical cases will be very nearly equal to the cross section of the flexible core, in square centimeters, the voltage induced over the length dl of the coil will be

$$de_s = A \times n' \times dl \times \frac{dH_t}{dt} \times 10^{-8} \text{ volts} \quad (4)$$

and the voltage produced by the whole coil, forming a closed path, will be

$$e_s = A \times n' \times \oint \frac{dH_t}{dt} dl \times 10^{-8} \text{ volts} \quad (5)$$

Differentiating equation 3 with respect to time results in

$$\oint \frac{dH_t}{dt} \times dl = 0.4\pi \frac{di}{dt} \quad (6)$$

and substituting this into equation 5 gives

$$e_s = A \times n' \times 0.4\pi \frac{di}{dt} \times 10^{-8} \text{ volts} \quad (7)$$

which is independent of the position and length of the loop.

To obtain an idea of the order of magnitude of the voltages that can be expected, suppose we wind number 30 wire on a rubber tubing of one square centimeter cross section (about $\frac{9}{16}$ inch diameter). Number 30 enamel will give about 90 turns per inch, or 35 turns per centimeter, if we use a single-layer winding. Suppose that a sinusoidal current of 1,000 (rms) amperes with a frequency of 60 cycles per second is made to pass through a toroid made of this tubing. Considering the fact that the maximum rate of change of a sinusoidally varying quantity equals $2\pi f$ times the amplitude, the rms value of the induced voltage will be

$$e_s = 1 \times 35 \times 0.4\pi \times 1,000 \times 2\pi 60 \times 10^{-8} = 0.166 \text{ volt} \quad (7a)$$

The production of one volt will, therefore, require about 6,000 amperes at 60 cycles per second.

However, the voltage calculated according to equation 7 under the assumption of a sinusoidal current, as in equation 7a, is not the one to be measured, as explained earlier; the integrating cir-



Figure 4. Arrangement of return lead to eliminate effect of magnetic fields not due to current to be measured

cuit not only reduces the actual voltage available for measuring to about five per cent of the voltage induced in the toroid, but also makes it appear across a circuit element having a high impedance compared with the impedance of the usual low-range rms voltmeter. It is, therefore, quite obvious that an amplifier will be needed to accomplish the measurement. It is of importance that this amplifier have as flat a response as possible, if the output of it is to be used for the operation of an oscillograph, although there is nothing gained by extending the frequency range beyond that of the oscillograph. For a string oscillograph a flat response of the amplifier from 60 to 3,000 cycles will, therefore, be entirely satisfactory. Figure 3 shows the diagram of an amplifier which has been found satisfactory for the purpose. Further refinements, such as inverse feedback, can, of course, be introduced to increase the accuracy of the measurement or to improve the stability and permanency of calibration. The need for these will be dictated by the nature of the problem with which one has to deal. Examination of the diagram shows that the integrating circuit is incorporated into the input circuit of the amplifier. The voltage across the integrating capacitor is applied to a 6F5; the output of this tube is fed to a 6N7 which serves as amplifier and phase inverter, so that the pair of output tubes, 2A3's, receives essentially a push-pull signal. The secondary winding of the output transformer has several taps, so that a proper match with the load can be accomplished. Any high-quality standard amplifier, to which the special integrating circuit has been added, can, of course, be used in place of the one shown.

Calibration of the device is relatively simple. In contrast to a shunt method, it is not necessary to have a calibrating current available of the same order of magnitude as the currents to be measured. By linking the calibrating current several times with the toroid coil, its magnitude can be reduced to almost any desired value. Thus, if, for instance, a shunt coil of a d-c machine with a known number of turns is available, currents of the order of a few amperes can be used for calibration. Instead of using a known current for calibration, it is also possible to calculate the voltage which will be induced by a given current of sinusoidal wave shape and known frequency, as shown in equation 7a. For the toroid to which this equation refers, we had found a voltage of 166 millivolts induced by a 1,000 ampere rms, 60-cycle per second sinusoidal current. By applying 166 millivolts, 60 cycles per second, obtained from any convenient 60-cycle source (such as a voltage divider) to the given integrating circuit and amplifier, and observing the output of the amplifier, calibration is obtained. Because of the action of the integrating circuit, as explained previously, the calibration will be correct for any wave shape.

An interesting detail in connection with the leads of the toroid coil should be pointed out. During the initial experiments, when the leads were brought out as in Figure 2, it was noticed that the voltage induced in the coil was not independent of the position of the coil with respect to the conductor. At first it was thought that this was due to the cross section of the toroid not being small enough. The true explanation, however, is that the toroid itself forms a loop, and any field will induce a voltage in it, regardless of whether a current passes through it or not. As soon as this was recognized as the cause, the remedy was obvious: one end of the winding should be brought back along or, ideally, on the axis of the helix, as shown in Figure 4. As soon as this was done, the position of the loop no longer had influence on the magnitude of the induced voltage. Another way to accomplish the same result at the same time increasing the output voltage, is to wind another layer of turns on the toroid, progressing with this layer in the opposite direction.

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Design Features of Generators for Diesel-Electric Switcher Locomotives

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MEMBER AIEE

Synopsis: Simplicity and reliability have been kept foremost in generators recently developed for Diesel-electric switcher locomotives ranging from ten to 80 tons. New motors and control equipment have been developed at the same time. This paper deals especially with the generators, their electrical and mechanical features, and performance characteristics, both as power generators and as motors for engine starting from the locomotive battery. Operating fundamentally as self-excited generators, separate exciters have been eliminated. The simplicity of the generator windings has allowed corresponding simplicity of control circuits.

THE Diesel-electric-locomotive generator is part of a portable power plant. This power plant is built into the locomotive, and, if it does not function correctly, the locomotive does not do its work properly. This power plant must be reliable and controlled easily under variable conditions of weather, location, motion, and frequently varying load.

Mechanical and electrical simplicity and durability are very desirable features if one wishes to obtain continued and reliable service with operators that are not always acquainted thoroughly with electrical equipment. Simplicity of the control scheme is also dependent mainly on the generator performance characteristics and windings.

The purpose of this paper is to explain the electrical and mechanical features of

some of the recent generators that have been developed for industrial switcher locomotives and railway switchers up to approximately 80 tons.

Mechanical Requirements

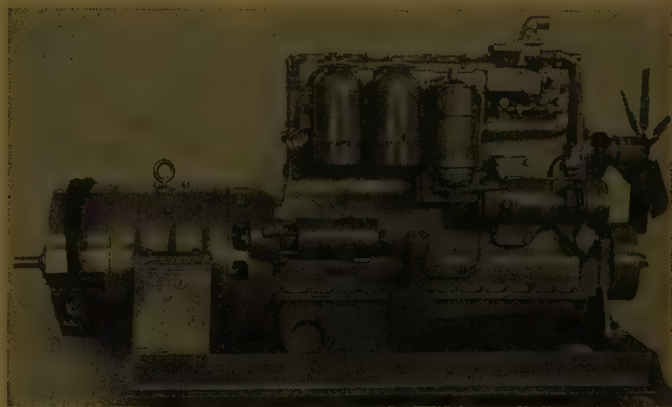
Generators with a single bearing at the commutator end have been adopted as standard for the sake of mechanical design simplicity. The armature is supported at the engine end by the engine

tional flexibility. This is not desirable as the generator armature should act as a flywheel for the engine, thus allowing the engine flywheel to be cut down in weight merely to what is necessary for coupling purposes. When the generator stator is rigidly connected to the engine by being bolted to a bell housing, the whole power plant is mounted with a three-point support (see Figure 1). Two of these support points are at the sides of the generator frame, and the third point is at the opposite end of the engine. This three-point support makes it easy to provide a flexible mounting for the complete power plant when resilient supports at these three mounting points are supplied.

Another common method of combining the engine and generator into a unit power plant is that of supporting both on a rigid bedplate (see Figure 3). Means

Figure 1. Engine-generator unit arranged for three-point support

1,800 rpm, 140-horsepower net input



crankshaft. This arrangement uses the smallest number of parts and provides for the closest coupling between the generator and engine.

Steel-disk couplings, flexible to angular misalignment, are employed on the higher-speed engine-generator combinations, where the generator stator is bolted solidly to an engine bell housing. The coupling flexibility takes care of slight inaccuracies in machining that may prevent the engine shaft and the generator shaft from being exactly in line. The steel-disk coupling does not have rota-

are provided for aligning the generator shaft accurately with the engine crankshaft before the generator frame feet are bolted solidly to the bedplate and doweled in position.

The first impression that the layman gets, in looking at the engine-generator set for a Diesel-electric locomotive, is that the generator is much smaller than the engine. This, however, is not something for the generator designer to boast about. It is due to the inherent fact that the really active material of the engine requires a lot of attachments and

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Figure 2. A generator used on 25- to 50-ton locomotives

1,000 rpm, 170-horsepower net input

auxiliaries for its proper functioning, whereas the electric generator is nearly all active material of either electric or magnetic circuits.

How large should a generator be to operate with a given engine? One engineer expressed it by saying that the generator should be able to do anything that the engine will do. This is a rough but simple way of stating it and is a very general guide. The Diesel engine and the d-c electric generator are such different types of power machines, however, that there is more to it than such a simple statement. More specifically, the generator size is determined usually by the torque and speed that the engine can supply to it continuously and by the maximum volts and maximum amperes demanded of the generator by the electric driving motors in order to meet the required locomotive performance. The most economical generator size is obtained when both it and the driving motors are designed at the same time, with proper regard to voltage and ampere values.

Naturally, generators directly con-

nected to high-speed engines are smaller than those for slow-speed engines. Usually, engines with operating speeds below 1,500 rpm are called slow-speed, and those above 1,500, high-speed, for locomotive service.

Generators designed for this service are usually all new, so that there is a freedom of choice of the ratio of diameter to length. The result is always a compromise between the short and fat and the long and skinny types. This compromise is the result of consideration of the economical ratio of diameter to length of the armature core, the diameter that will best suit mounting with the given engine and a minimum over-all length of the engine-generator set. Another factor affecting this ratio is the critical speed of the rotating members of the engine and generator taken together. In some cases the diameter of the generator armature has been made smaller than it would have been, for the other reasons just mentioned, in order to reduce the armature WR^2 and keep away from critical speed vibrations that might cause dangerous stresses in the rotating parts.

This type of generator is well suited to effective self-ventilation by a fan on the armature shaft. The generator is nearly always mounted in a protected compartment, so that it is not necessary to enclose the space around the commutator other than to provide a cover over the top to protect the commutator and brush holders from falling objects. The arrangement shown in Figure 3 is especially effective in providing clean air for cooling the generator and using the air exhausted from it to assist in ventilating the engine compartment. A vertical partition in the enclosing hood (not shown in Figure 3) is located at the center of the generator body and prevents hot air from the engine compartment being used to ventilate the generator. In this case, the blower

for force-ventilating the traction motors and control, the air compressor, and the auxiliary generator are arranged conveniently to be driven from a shaft extension at the commutator end without in any way preventing easy access to the brush holders and commutator.

Electrically, the generator must act as a generator for supplying power to the motors and also as a battery-driven motor for cranking the engine. These two types of electrical performance will be considered under separate headings.

Performance Characteristics as a Generator

When the performance curves of a Diesel-electric locomotive generator are discussed, we must always keep in mind the fact that it is supplied with a rather definitely limited amount of power input. Unlike the ordinary powerhouse lighting generator, the voltage cannot be kept constant over a wide range of ampere load. This is due to the fact that an increase in amperes, without a corresponding decrease in voltage, means an increase in power beyond the ability of the engine. The ideal generator-regulation characteristic is one that supplies just the right voltage at any ampere load and speed, so that its output plus the losses will balance exactly the power supplied to the generator. In other words, the problem of the generator regulation is to make its power input balance the output of the engine at any ampere load demanded by the traction motors and at any speed and throttle opening of the engine.

Many types of separate exciters and field-current regulators have been considered for properly adjusting the generator field strength at different ampere loads, so that just the right voltage is obtained. Many of these schemes are too complicated or introduce factors of unreliability or additional cost or maintenance to have found favor for use on small- and medium-size switcher locomotives.

The type of generator that gives a close approximation of the ideal regulation, and at the same time an ultimate in simplicity, is a modification of the ordinary self-excited d-c generator. The modifications consist of adding a small percentage of separate excitation from the locomotive battery and a special unsymmetrical shaping of the main pole faces. The unsymmetrical main-pole shaping is allowed, because the rotation is always in the same direction. The object of this pole-face shaping is to change the load saturation curves with respect to the

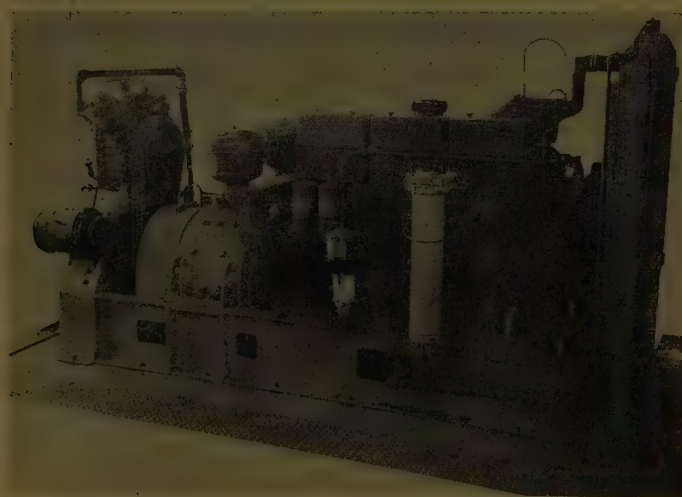


Figure 3. A locomotive power-unit arrangement that affords easy access and good ventilation for both generator and engine

1,000 rpm, 295-horsepower net input



Figure 4. 65-ton Diesel-electric railway locomotive

no-load saturation curve, so that the field excitation provided by the self-excited and battery fields will approach closely that required for the ideal voltage regulation. This effect results from a compounding action that counteracts the effect of armature reaction to the desired degree.

Figure 6 shows test voltage and speed regulations of a generator driven by a Diesel engine delivering 275 net horsepower to the generator at 1,200 rpm. From *F* to *E* on the speed curve, or *C* to *B* on the voltage curve, the generator is absorbing full-throttle power from the engine. Over this part of the curve the engine speed is determined by the load the generator demands from it. Since the speed is approximately constant, the horsepower input is also approximately constant.

At *E* the engine governor starts to operate, and the speed from *E* to *D* is determined by the governor and not the generator load. The part of the voltage curve *BA* is the voltage that the generator will produce at this governed speed with the same field setting as for the full-throttle operation from *C* to *B*. Point *B* is called the "unloading point." Most of the operation of a switcher locomotive will be over the voltage range from *C* to *B*, and, when maximum power and speed are required over this range, the operator will use wide-open throttle. Actually, in switching service, or even in so-called "transfer service," full throttle is not used for a very long period of time. At partial-throttle positions, both speed and voltage are lower at any given amperes. Since amperes represent locomotive tractive effort, partial throttle and lower voltage simply mean lower speed at a given tractive effort.

In cases where the locomotive is required to do high-speed service at light

tractive efforts, it is desirable to provide a second field setting so that a higher-voltage unloading point will be obtained, as at *J*. This is obtained by decreasing the amount of resistance in the self-excited field circuit when the voltage has increased to *G*. This change is conveniently made with a voltage relay. This permits full-throttle loading with speed *H₁-K* and voltage *G₁-J*. At *K* the engine governor begins to operate, and at lower ampere loads the speed is determined by the governor, and the generator produces voltage *J-L*.

It is obvious that, if full power were taken from the engine at very low amperes, the voltage required would be very high. The minimum amperes for which the unloading point is set must be chosen with due respect to the maximum voltage that the generator commutator is good for and the voltage required by the traction motors to provide the specified high-speed performance of the locomotive.

It should be kept in mind that the performance shown in Figure 6 is the maximum performance of the power plant, and that most of the operation will be at less power and correspondingly lower speed and volts. This lower power performance will be a result of the operator not using full throttle. Diesel engines for locomotive service are not intended for full-throttle operation continuously. The generator could operate continuously between two limits of continuous rating. The upper limit of continuous ampere rating is determined by the heating of the main current-carrying parts, such as armature windings, commutating field windings, and commutator; the minimum limit, by heating of the self-excited field which has increased amperes and resulting increased heating as voltage rises.

The battery field uses only a few amperes from the battery and is left on at all loads. The purpose of this separately excited battery field is to provide a positive flux in the magnetic circuit and



Figure 5. Ten-ton Diesel-electric industrial switcher locomotive

definite voltages at the lower operating speeds. The special shaping of the main pole faces is of assistance to the battery field in this respect.

Performance Characteristics as a Starting Motor

The most convenient method of engine cranking is to use the generator as a starting motor. This eliminates the necessity for a separate starting motor, its mounting and gearing to the engine flywheel.

A series motor characteristic is necessary to provide both high breakaway torque and the required firing speed and torque. A separate series main-field winding is built into the generator especially for this purpose. At starting, this field winding is connected in series with the armature and commutating field. This starting-motor circuit is connected directly to the battery terminals until the engine fires.

Engine builders are usually in a position to furnish information on the break-away torque required to start the engine

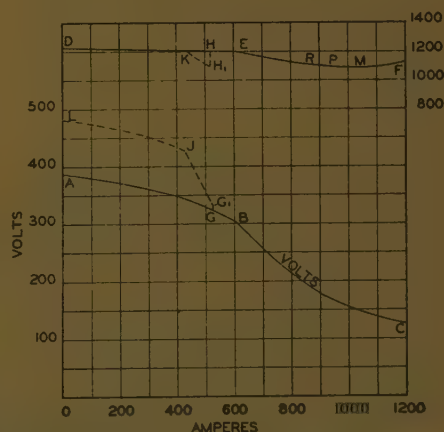


Figure 6. Typical generator-voltage and speed-regulation curves

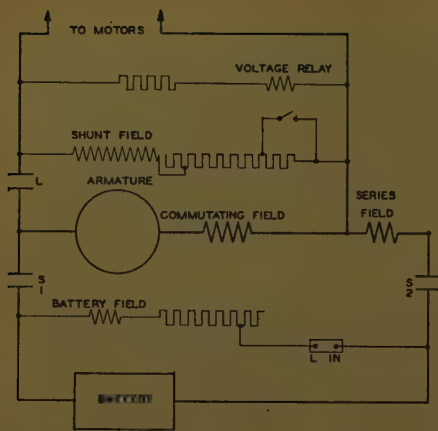


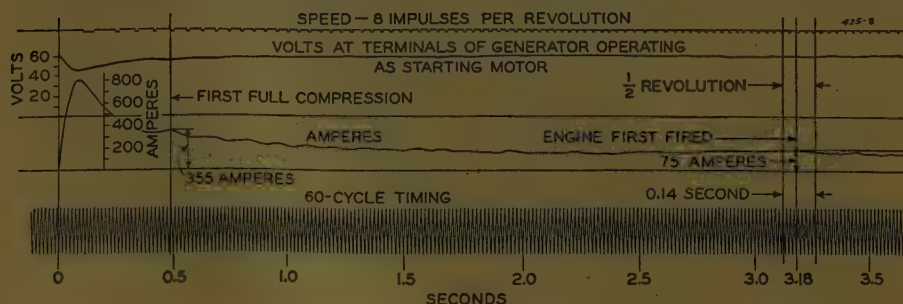
Figure 7. Schematic control diagram showing simplicity of circuits

from zero speed and the speed and torque, required at firing. The best method of obtaining this information, with all mechanically driven auxiliaries connected as in service, is by means of an oscillographic test recording volts, amperes, and speed of the generator acting as a starting motor. The values of speed, torque, current, and volts during starting are such rapid transients that ordinary meter readings are very uncertain.

Figure 8 is a tracing of a typical oscillogram of such an engine-starting test. A 60-cycle timing wave was included in addition to the values of volts, speed, and amperes. In this case speed was recorded by a disk mounted on the engine shaft that made eight contacts per revolution. The speed at any point along the curve can be obtained by finding the number of cycles of the timing wave corresponding to a certain number of the speed-indicating impulses. For example, at the firing point, four speed indications or one-half revolution correspond to 8.4 divisions on the 60-cycle timing wave, or 214 rpm.

In this oscillogram the current record is used to measure instantaneous torque. The actual torque is obtained by referring to an ampere-torque curve, previously obtained from factory test of the generator as a series motor. The initial inrush

Figure 8. Typical oscillogram of test to determine engine-starting requirements



of current is not a measure of breakaway torque, since this current is limited only by the impedance of the circuit and would represent more torque than is required to start the engine turning. The ripples in the current curve indicate variations of torque due to the cylinder compressions. The maximum value of the first full compression has been taken as the current corresponding to maximum breakaway torque. This value, scaled from the oscillograph, is 355 amperes. From the ampere-torque curve for the generator used in this test, this current corresponds to a torque of 1,040 pound-feet.

After breakaway, acceleration continued up to a time of approximately 2.0 seconds, after which the speed was nearly constant, as indicated by the equal spacing of the speed-indicator impulses.

When the engine fired, a sudden decrease in current took place. The point is accurately determined when a tangent is drawn to the tops of the ripples of the

Table I

Commutating-Field Winding	Volts	Amperes
In	27.5	375
Out	34.5	325

current curve just ahead of this decrease. The engine firing in this case started at 3.18 seconds after 9.15 revolutions, at a speed of 214 rpm at 315 pound-feet torque. A number of such tests should be taken under varied conditions of temperature, engine-oil viscosity, and length of time the engine has been standing. This information is necessary to provide data for designing the series-field winding of a new generator and to determine the characteristics of the battery that will be required to insure engine starting under these conditions.

Figure 9 is a typical curve of a generator operating as a series starting motor obtained from factory test under steady-state conditions. The curve is plotted as shown so that either breakaway or firing torque can be read from it and also the voltages required. The torque curve was determined when pounds were read

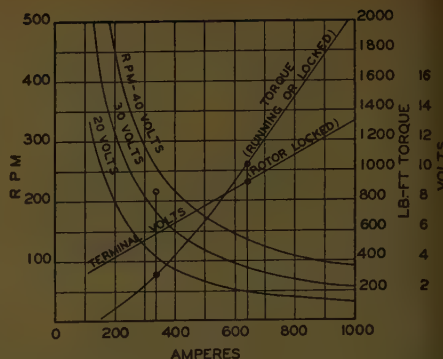


Figure 9. Typical curve of generator operating as a series starting motor

at the end of an arm clamped to the shaft under locked condition. This was checked when torque was calculated from inputs, speeds, and losses while it ran at 30 volts. Theoretically, the torque, when running, should be slightly less than the locked torque, but the speed is low and the field strength comparatively low in comparison with the operating conditions as a generator, so that the rotational losses are practically negligible. The running and locked torques are, therefore, plotted as one curve for simplification.

To illustrate the use of this curve, let us use the values of torques and speed obtained from the oscillograph test and determine what values of volt and amperes this generator will require to start the engine. (Incidentally, the oscillograph test was taken on a different type of generator prior to the development of this one.) The breakaway torque of 1,040 will require 640 amperes and 9.2 terminal volts. The firing torque of 315 at 214 rpm will require 335 amperes and a terminal voltage of 35. The latter value is obtained by interpolating between the 30- and 40-volt speed curves.

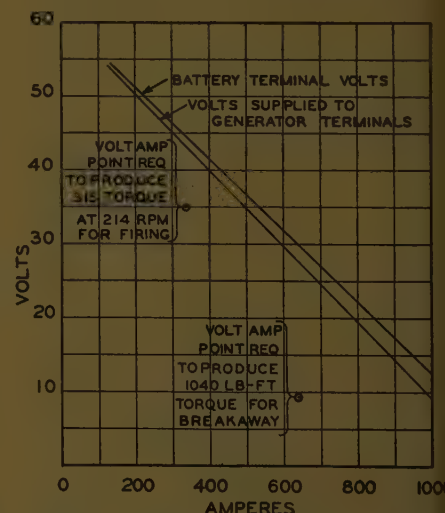


Figure 10. Battery volt-ampere curve with volt-ampere points for a given engine's starting requirements

Figure 10 shows these volt-ampere points located on the same plot with the voltage of a proposed battery. The battery-voltage curves were obtained from the battery manufacturer's data. Such data are usually given in volts per cell and amperes per positive plate. It is plotted here as total amperes and terminal volts for the battery considered. The volts drop from battery to generator terminals must be accounted for. This drop includes that of such switches and contactors as are in the starting circuit. It is advisable to utilize liberal cable size in this circuit and to keep the lengths as short as possible, because a few volts drop multiplied by the amperes required represent a large percentage of the power being drawn from the battery.

If the volt-ampere points for break-away and firing lie well below the generator-terminal voltage curve, then the battery proposed can be considered as adequate.

The question is sometimes asked as to why the commutating-field winding is not omitted when the generator is used as a starting motor at the comparatively low battery voltage. This would give a lower-resistance starting motor, and, at first thought, this would require less battery volts at a required speed and torque. Actually, this is not the case. For example, tests on a generator, used to start an engine which required a firing torque of 200 pounds-feet at 200 rpm, showed the volt-ampere requirements given in Table I.

Although the amperes required are 13 per cent less, the voltage is 25 per cent greater with the commutating-field winding omitted and would require a higher-voltage battery. The reason for this is the familiar effect of an undercompensated commutating field reducing the speed of a motor. In the case of complete omission of the commutating-field excitation with the poles still in place, the undercompensating effect is very marked and produces the unfavorable change in required volts and amperes shown in Table I.

Conclusion

Generators having the mechanical features and the electrical performance described in this article are being applied to many sizes of industrial and railway switching locomotives at the present time. In addition to use on railroads and in industrial plants, many are being used by the Army and Navy in the United States and overseas. Others are being supplied to our allies. Their simplicity

Diesel-Electric Switching-Locomotive Application by Means of Nomographic Charts

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Synopsis: The application of switching locomotives involves calculations of locomotive performance under given conditions of grade, train weight, and length of run. Such calculations can be made quickly by nomographic charts. Equipment heating limitations on Diesel-electric and electric locomotives can also be checked by elements added to the nomograms. The theory and the method of construction of such charts are described in the paper.

IN the process of determining applicability of Diesel-electric locomotives to railroad and industrial switching services, it is often necessary to determine whether or not the haulage of a given train up a grade of known length and severity is possible without exceeding the locomotive-equipment heating limitations.

The performance of such a haul is limited by wheel-to-rail adhesion, or by heating of the electric (traction motors and generators) or the engine equipment, or by both of these limitations.

Since switching service—be it industrial or railroad—usually comprises relatively short movements at full-load rating of the locomotive-engine equipment, coupled with idle periods, the engine

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equipment is, in general, applied on an intermittent-rating basis. Thus, a nominal 500-horsepower unit is suitable for sustained operation of the engine equipment at 500-horsepower output for but a limited period of time. This may be a period of one-half hour, or one hour, after which the load must be reduced to a fraction of the rating for a definite period of time before the nominal rating load can be carried again.

Likewise, the traction motors and generators are limited to definite-period loading, depending upon the heating characteristics of the machines under various conditions of loading.

The conventional speed-tractive-effort characteristic of the Diesel-electric switching locomotive, by itself, gives no information as to the service that can be performed with the locomotive without exceeding its equipment limitations, particularly in the high-tractive-effort low-speed portions of the characteristic where electric-equipment heating is limiting.

The speed-tractive-effort characteristic can be combined with the time-limitation characteristics, both of the engine and the electric equipment, on a nomographic chart which can be used to determine graphically and quickly whether or not a particular locomotive can handle safely a given train under known conditions of grade and length of grade.

The trailing tonnage that can be

and reliability will be important factors in prompt movement of supplies and men in the many locations where they will be used.

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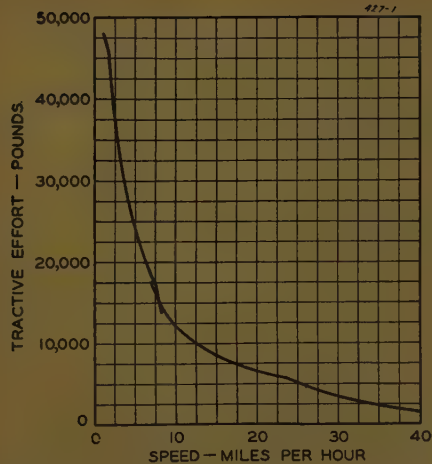


Figure 1. Speed-tractive-effort characteristic for 80-ton 500-horsepower Diesel-electric switching locomotive

handled by a locomotive at a definite speed on a given grade is determined by solution of the equation

$$W_t = \frac{T - W_L(R_L + 20G)}{(R_t + 20G)} \quad (1)$$

in which

- T = tractive effort in pounds of the locomotive at the given speed
- R_L = resistance of the locomotive in pounds per ton of locomotive weight at the given speed
- R_t = train resistance in pounds per ton of train weight at the given speed
- W_t = weight of trailing train in tons
- W_L = weight of locomotive in tons
- G = grade in per cent

The train resistance varies with the individual weights of cars in the train, but, since unjustifiable complications in the calculations would be involved were this variation considered, a fixed value of train resistance based on experience is assumed in the following. This is taken at 8.5 pounds per ton. The value of R_L , resistance of the locomotive,¹ is, however, easily determined for different speeds by the equation

$$R_L = 1.3 + \frac{29}{W} + 0.03V + \frac{0.0024AV^2}{W_h} \quad (2)$$

in which

- R_L = resistance of locomotive in pounds per ton
- W = weight per locomotive axle in tons
- N = number of locomotive axles
- V = speed in miles per hour
- A = cross section of locomotive in square feet
- = 105 for 50-ton locomotives
- = 110 for 70-ton locomotives
- = 120 for 100-ton locomotives

By means of the two equations, given in the foregoing, and the speed-tractive-

effort characteristic curve applying to the particular locomotive (Figure 1 shows such a characteristic for a 500-horsepower 80-ton locomotive), a speed, grade, and trailing tons can be indicated as in Table I.

This table can be plotted in the form of a three-element nomogram with speed, grade, and trailing tons as the three elements. While the nomogram may be worked out analytically, the authors suggest that the graphical method of constructing the nomogram, as described in the following, is simpler and less tedious for those not skilled in setting up nomograms in general.

On any convenient size of paper the G scale is drawn in at the left-hand side of the paper, perpendicular to the base ordinate, while the W scale is erected perpendicular to the base line near the right-hand side of the paper (Figure 2). The authors suggest a minimum distance of 10 inches between the G and W scales and a length of 20 inches for the G and W scales for charts for locomotives up to 1,000-horsepower rating.

The W scale is marked off in a rectilinear scale, so that the maximum tonnage shown in Table I falls near the top of the sheet with the value of 0 tons at the base line.

On the G scale the value of 1.0 per cent grade is arbitrarily located one half of the length of the G -scale line above the base line. The value of zero per cent grade is taken at the base line.

The S scale is located as follows:

From the table select a value of tonnage that can be handled at a low speed—5.0 miles per hour—on level grade, and draw the construction line AB (Figure 2). From the table select a value of tonnage, corresponding to the same speed previously used—5.0 miles per hour in the present case—that can be hauled on a 1.0 per cent grade. Draw the construction line CD . The intersection of AB and CD determines one point on the S scale. A second point corresponding to a higher speed can be determined in a similar manner when two combinations of speed, tonnage, and grade are selected from Table I. The S scale is then drawn in, as shown, as a straight line.

The G scale may be calibrated up to the maximum value of grade desired when the value of W is calculated for assumed values of G at 5.0 miles per hour by equation 1, and when the values of G are located on the scale by means of a straightedge from the value of W on the W scale through the 5.0 mile-per-hour point on the S scale.

Similarly, the S scale may be calibrated

by laying a straightedge between the values of tonnage and grade given in Table I.

The upper end of the S scale may be taken at a speed point corresponding to 25 per cent adhesion tractive effort on the speed-tractive-effort characteristic. In the example selected 25 per cent of the locomotive weight is 40,000 pounds and the speed corresponding to this tractive effort from Figure 1 is 2.2 miles per hour.

The elements of the chart, which are required to indicate engine- and electric-equipment heating limitations, are added as described in the following procedure.

At the point on the S scale corresponding to 25 per cent adhesion speed, a perpendicular AB in Figure 3 is erected. Another line CD , Figure 3, is erected perpendicular to the S scale at the locomotive speed corresponding to the short-time limitation on the electric equipment which corresponds to the short-time limitation on the engine equipment. In the example selected, the engine equipment is limited to operation at 500 horsepower for 30 minutes, and the speed of 3.5 miles per hour corresponds to a 30-minute rating on the electric equipment for an initial winding temperature of 100 degrees centigrade and a final winding temperature (at the end of 30 minutes) of 160 degrees centigrade.

The point D is projected over to the line AB , parallel to the S scale to the point E . The line AE is then laid off on a logarithmic scale in minutes with the value of one at A and 30 at E .

The points F , G , and H are laid in on

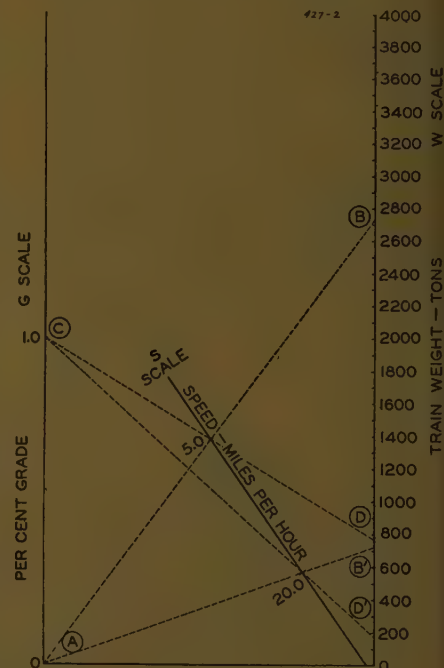


Figure 2. Construction of speed-grade-train-weight nomogram

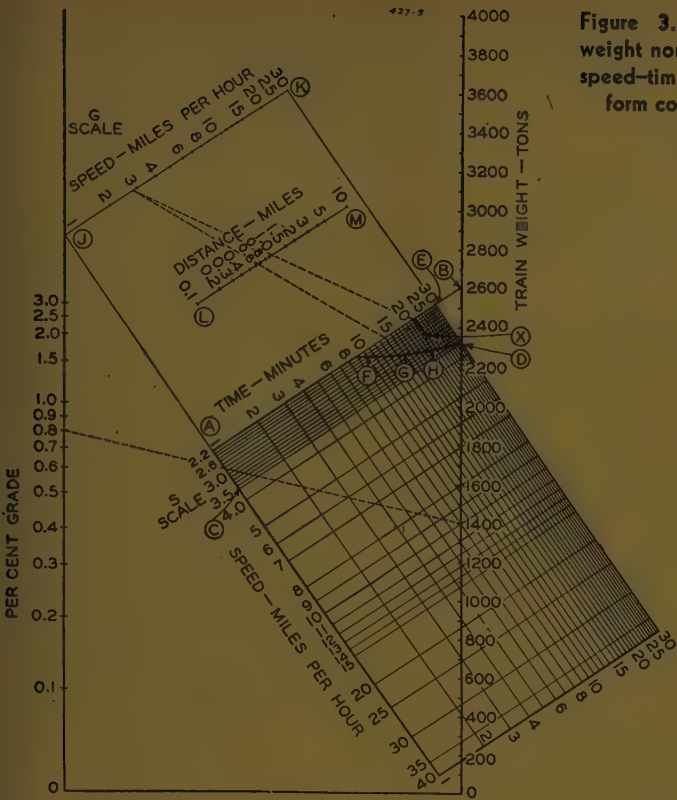


Figure 3. Speed-grade-train-weight nomogram combined with speed-time-distance nomogram to form complete working chart

Table I. Trailing Tonnages

Speed Miles Per Hour	Level	Per Cent Grade (Compensated)			
		0.5	1.0	1.5	2.0
3.3	...	3,737	1,674	1,057	762
5.0	...	2,767	1,227	768	547
7.5	...	1,923	840	516	361
10.0	...	1,420	609	367	251
15.0	...	974	404	234	152
20.0	...	731	292	161	98
25.0	...	540	204	104	56
30.0	...	340	113	45	12
35.0	...	193	45		
40.0	...	100			

Resistance based on 8.5 pounds per ton, motors blown.

Tonnages do not include weight of locomotive.

the 10-, 15-, and 20-minute lines at the speeds corresponding to the tractive efforts to which these short-time ratings conform. The line *FGHD* indicates the limitations imposed by safe heating of the electric equipment.

The line *JK* is now drawn in as shown, perpendicular to the *S* scale at *J*, and calibrated in a log scale in speed in miles per hour with the value of one at *J* and the value of 30 directly opposite the 30-minute mark on *AB*.

The line *LM* is erected midway between *JK* and *AB* and calibrated in a log scale in miles fixing the 0.1-mile and 10-mile points with a straightedge laid between *JK* and *AB* at the points three miles per hour and two minutes (for 0.1 mile) and 30 miles per hour and 20 minutes (for ten miles).

The elements *AE*, *LM*, and *JK* are a nomographic plot of the equation

$$M = 0.01667 \times S \times T \quad (3)$$

in which

M = distance in miles
S = speed in miles per hour
T = time in minutes

The chart is now ready for use.

As an example of its use, it is desired to determine whether the haulage of a 1,400-ton train up an 0.8 per cent grade one mile long will cause overheating of the engine or electric equipment on the 80-ton 500-horsepower locomotive for which the chart has been drawn.

A straightedge laid between 0.8 on the *G* scale and 1,400 on the *W* scale crosses the *S* scale at 2.8 miles per hour.

A straightedge laid across the points 2.8 on line *JK* and 1.0 on line *LM* intersects the time scale at 21.5 minutes. A line drawn from 2.8 on, and perpendicular to, the *S* scale intersects the 21.5-minute line at *X*, and, since this point lies above the electric-equipment heating line *FGHD*, the indication is that the

electric equipment will be overheated in performing the given service. It may be noted that the line from 2.8 miles per hour on the *S* scale to *X* intersects the line *FGH* at 14 minutes. A straightedge, laid between the 14-minute point on line *AB* and the 2.8 point on *JK*, intersects the *M* scale at 0.66 mile, indicating that haulage of the 1,400-ton train on an 0.8 per cent grade should be limited to a distance of 0.66 mile, if the electric equipment is not to be overheated.

By obvious cut-and-try methods it can be determined that a train of 1,285 tons trailing is the maximum that can be handled on the 0.8 grade, one mile in length, without exceeding the permissible temperature rise in the electric equipment.

If the intersection of the speed line from the *S* scale with the time line falls below the electric-equipment heating-limitation line, but to the right of the 30-minute line, overheating of the engine equipment is indicated.

If the straightedge between the *G* scale and *W* scale falls across the *S* scale at a point above and to the left of the point *A*, a high value of adhesion (greater than 25 per cent) and the likelihood of wheel slippage are indicated.

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Symmetrical-Components Analysis of the Four-Phase System

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Synopsis: Symmetrical-components concepts are developed for the currents, voltages, and impedances of a four-phase system, and formulas are given for various types of short circuits. The idea of symmetry among the members of each set is based on the angular displacement between the members of the set, rather than that of phase rotation which fits the three-phase case very nicely but is inadequate for the four-phase case.

Aside from its possible value for four-phase problems, which are rather rare, the paper is presented here in the expectation of an additional benefit, namely, that the parallelisms and contrasts between the four-phase and the three-phase formulas may throw further light on the general theory and applications of symmetrical components.

THE highly developed automotive art—model of American efficiency in production—has taught the public to expect that the factory must be specially tooled up for each new model. The philosophy of tooling is such common knowledge in the mechanical arts that, even though many an operation could be carried out with hammer, file, and screw driver, many a mechanic will frequently be seen making a special tool for an odd operation, as requiring less time in the end. The same philosophic principle holds in all the arts, electrical as well as mechanical; and such an experience in electrical engineering, with a conscious philosophy of tooling, led to the work which forms the subject matter of this paper.

The author had occasion to analyze the performance characteristics of an existing two-phase system if converted to a five-wire four-phase system. The attempt was made first by elementary methods, using such common tools as Kirchhoff's laws, but the problem involved unknown mutual impedances, and additionally the equations tended to be lengthy and burdensome, and each new problem meant going through a similar distasteful operation all over again. It was then

thought that on the whole the work would be much less and the results more dependable if a tool was developed in the form of a four-phase symmetrical-components method of analysis. This was done, and the results fully justified the expectations. The analysis became very systematic and straight forward; the impedances, such as could be estimated with some confidence; and the resulting formulas, such as could be interpreted and checked physically. It was then thought that it might be worth while to put this system of analysis on public record, not only for use on those few occasions when four-phase system problems may be encountered, but also for its technical and educational value, as a further illustration of the power of the symmetrical-components concept as a tool in the analysis of electrical systems.

Those familiar with the three-phase technique will be interested in observing the resemblances and the differences between the three-phase and the four-phase techniques.¹⁻³

Concept of Symmetrical Components in the Four-Phase System

The conventional concept of symmetrical components of three-phase system—positive-negative-, and zero-phase-sequence components—is peculiar to the three-phase circuit and not very adaptable to a system with greater number of phases, because a four-phase system must have four components (n -phase system n components), and the concept of positive-, negative-, and zero-phase-sequence components offers us no clue as to how to find an appropriate fourth component for the four-phase system.

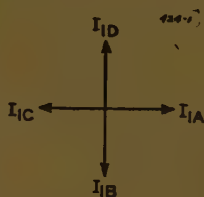


Figure 1. Symmetrical set of vectors, I_1

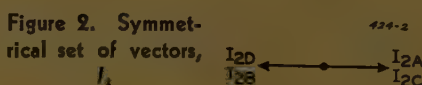


Figure 2. Symmetrical set of vectors, I_2

If, instead of considering the direction of rotation as the distinguishing mark of a symmetrical set of vectors, we consider the magnitude of the characteristic angle between the vectors of the adjacent phases as the distinguishing mark, we obtain a rule that enables us to define the symmetrical components of a system of any number of phases. Thus, if the angle between adjacent phases is θ for the normal symmetrical set of vectors of the system, then a set in which the vectors succeed each other at intervals of 2θ constitutes a second symmetrical set; one with intervals of 3θ , a third symmetrical set; and so forth. The negative-sequence set of the three-phase system corresponds to the set having the characteristic angle of 2θ . Since, in the n -phase system, θ equals $360/n$ degrees, the n th set of symmetrical vectors will have the characteristic angle $n(360/n)$, or just 360 degrees, which is equivalent to zero; that is, all of the vectors will be in phase with each other, like the zero-phase-sequence set of the three-phase system. The set $(n+1)$ turns out to be a duplication of set 1, $(n+2)$ a duplicate of set 2, and so forth, so that the n -phase system has only n distinct symmetrical components.

Accordingly, in a four-phase system (Figure 5), the consecutive phases of the normal symmetrical set of vectors I_1 are spaced 90 degrees apart (Figure 1); those of set I_2 , 2×90 degrees or 180 degrees apart (Figure 2); those of set I_3 , 3×90 degrees or 270 degrees apart (Figure 3); and those of set I_4 , 360 degrees, or what is equivalent to it, 0 degrees apart (Figure 4).

Evidently, the set I_1 (Figure 1) corresponds to the positive-phase-sequence set of three-phase systems: the set I_3 (Figure 3), to the negative-phase-sequence set; and the set I_4 (Figure 4), to the zero-phase-sequence set; but there is nothing like the set I_2 (Figure 2) in a three-phase system. The set I_2 has a similarity to the set I_4 , except for the important difference that, instead of a neutral return, the horizontal phases act as return to the vertical phases, and vice versa.

The difference in concepts leads also to a difference in notation. If we wish the subscript to represent the characteristic angle, then the set of vectors in Figure 3,

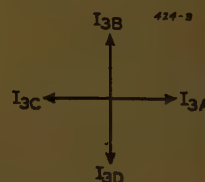


Figure 3. Symmetrical set of vectors, I_3

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Table I. Impedance Data

Bank G	Bank U	Primary	Total	
7,500-	7,500-	Lines	15,000-	
Kva Base	Kva Base	Kva Base	Kva Base	
(Per	(Per	(Per	(Per	
Cent)	Cent)	Cent)	Cent)	
Z_1	6.4.....	6.4.....	2.4.....	8.8
Z_2	75.....	75.....	75.....	75
Z_3	6.4.....	6.4.....	2.4.....	8.8
Z_0	75.....	Infinity.....	150.....	150

with the characteristic angle 3θ , is correctly marked as I_3 ; whereas, if phase rotation were to be the guide, we would have had to mark it I_2 , and the set I_4 as I_0 , conforming to the conventional notation for the negative- and zero-phase-sequence components of the three-phase circuit. This author feels that the three-phase notation is about as poorly adapted as the three-phase concept to the four-phase circuit, but, inasmuch as I_n has zero characteristic angle in all systems, we may use the conventional symbol I_0 for it. So in what follows, we shall refer to I_4 and E_4 as I_0 and E_0 .

Impedances to Sequence Currents

The types of symmetrical sets of currents already defined, and illustrated in Figures 1-4, define also the corresponding impedances (Z_1 , Z_2 , Z_3 , Z_0) for a four-phase system.

(a). Z_1 is the impedance of the circuit to the normal balanced four-phase currents of Figure 1. It is independent of the condition of the neutral—whether it be grounded or isolated, and even whether the mid-point of the vertical windings is joined with that of the horizontal windings. Phase A , however, must be joined with C , and B with D .

(b). Z_2 is the impedance offered to currents like those in Figure 2. As the horizontal and the vertical phases act as return circuits to each other, their mid-points must be tied together. Otherwise Z_2 will be infinity. The grounding or isolation of the common neutral makes no difference to Z_2 . Z_2 can be measured with single-phase voltage, connecting A to C as one terminal, and B to D as the other. The result must, of course, be expressed per phase.

To secure a low value of Z_2 , opposite phases must be well interlaced or closely coupled with each other. Depending on the presence or absence of such treatment in transformers, Z_2 may be as low as $Z_1/10$, or as high as $10 Z_1$.

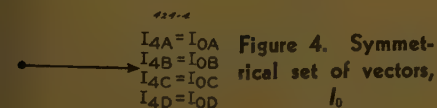
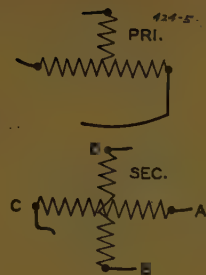
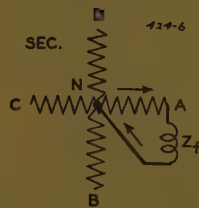
Figure 4. Symmetrical set of vectors, I_0 

Figure 6. Single-phase load, line-to-neutral

Figure 5. Four-phase supply system—three-phase primary, four-phase secondary connections



(c). Z_3 is the negative-phase-sequence impedance and has the same value as Z_1 for static circuits.

(d). Z_0 . If Figure 4 is compared with Figure 2, there is a certain similarity in the flow of currents, I_2 and I_0 , by virtue of which, Z_0 may have the same, or approximately the same, value as Z_2 . The important case in which this would not be true at all is the case of the isolated neutral, in which case I_0 cannot flow, and Z_0 must then be set down as infinity, while Z_2 may still have a very low value.

In most of the practical instances, therefore, the four-phase system is likely to have only two independent impedances, Z_1 and Z_0 ; although, in the general case, the static system will have three independent impedances, Z_1 , Z_2 , and Z_0 ; and the rotating machine, four.

In all of these cases, it is necessary to assume that, for any one set of currents, the corresponding set of impedance drops are also symmetrical in the same sense as those currents. If this is far from true, the value of symmetrical-components method of analysis is greatly reduced.

Symmetrical Components of Unsymmetrical Four-Phase Currents

Representing the four phases by letters, the symmetrical components by numbers, and with phase A as the reference phase,

$$I_1 = I_{1A} = (I_A + I_B/90^\circ + I_C/180^\circ + I_D/270^\circ)/4 \quad (1)$$

$$I_2 = I_{2A} = (I_A + I_B/2 \times 90^\circ + I_C/2 \times 180^\circ + I_D/2 \times 270^\circ)/4 \quad (2)$$

$$I_3 = I_{3A} = (I_A + I_B/3 \times 90^\circ + I_C/3 \times 180^\circ + I_D/3 \times 270^\circ)/4 \quad (3)$$

$$I_0 = I_{0A} = (I_A + I_B/4 \times 90^\circ + I_C/4 \times 180^\circ + I_D/4 \times 270^\circ)/4 \quad (4)$$

and inversely

$$\left. \begin{aligned} I_A &= I_1 + I_2 + I_3 + I_0 \\ I_B &= I_1/90^\circ + I_2/2 \times 90^\circ + I_3/3 \times 90^\circ + I_0/4 \times 90^\circ \\ &= I_1/90^\circ - I_2 + I_3/90^\circ + I_0 \\ I_C &= I_1/180^\circ + I_2/2 \times 180^\circ + I_3/3 \times 180^\circ + I_0/4 \times 180^\circ \\ &= -I_1 + I_2 - I_3 + I_0 \\ I_D &= I_1/270^\circ + I_2/2 \times 270^\circ + I_3/3 \times 270^\circ + I_0/4 \times 270^\circ \\ &= I_1/90^\circ - I_2 - I_3/90^\circ + I_0 \end{aligned} \right\} \quad (4.1)$$

These accord with Figures 1-4.

Equations analogous to 1-4.1 apply also to voltages.

We now apply these formulas to some representative unsymmetrical cases for use in short-circuit calculations.

SINGLE-PHASE LOAD FROM ONE LINE TO NEUTRAL: $A-N$

As line A (Figure 6) is the only one with current, all others zero,

$$I_A = I_A \text{ (given)}; I_B = 0; I_C = 0; I_D = 0$$

Therefore, in applying formulas 1-4, only the first term on the right needs consideration, and we obtain the result

$$I_1 = I_A/4; I_2 = I_A/4; I_3 = I_A/4; I_0 = I_A/4 \quad (5)$$

That is, in the loaded phase (phase A), all four components are equal and in phase. It can be verified that in the adjacent phases (B and D , idle), I_2 cancels I_0 , and I_1 cancels I_3 . In the opposite phase (C , also idle), I_1 cancels I_2 , and I_3 cancels I_0 . These relationships find a significance in the calculation of voltage drops. If the corresponding impedances are alike, where the currents cancel, so will the voltages; but, if the impedances are dissimilar, a net voltage change (with no net current) will result.

Table II

	Grounded Bank	
	Phase A (Per Cent)	Phase C (Per Cent)
(1) $I_1 Z_1$	(1.65/4) 8.8 = 3.63.....	3.63
(2) $I_2 Z_2$	(1.65/4) 75 = 31.....	-31
(3) $I_3 Z_3$	(1.65/4) 8.8 = 3.63.....	3.63
(4) $I_0 Z_0$	(1.65/4) 150 = 62.....	-62
(5) Total Drop.....	100	-85.7

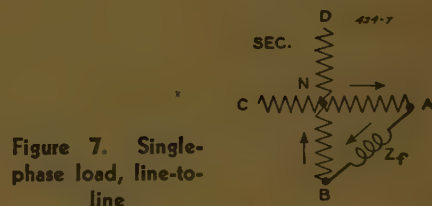


Figure 7. Single-phase load, line-to-line

SINGLE-PHASE LOAD ACROSS ADJACENT LINES: A-B

It is seen from Figure 7 that

$$I_A = I_A \text{ (given); } I_B = -I_A; I_C = 0; I_D = 0$$

Hence, only the first two right-hand terms of formulas 1-4 count, and we obtain the results

$$\left. \begin{aligned} I_1 &= \frac{1}{2\sqrt{2}} I_A / 45^\circ & (a) \\ I_2 &= \frac{1}{2} I_A & (b) \\ I_3 &= \frac{1}{2\sqrt{2}} I_A / 45^\circ & (c) \\ I_0 &= 0 & (d) \end{aligned} \right\} \quad (6)$$

SINGLE-PHASE LOAD ACROSS OPPOSITE LINES: A-C

From Figure 8

$$I_A = I_A \text{ (given); } I_B = 0; I_C = -I_A; I_D = 0$$

By equations 1-4

$$\left. \begin{aligned} I_1 &= 0.5 I_A \\ I_2 &= 0 \\ I_3 &= 0.5 I_A \\ I_0 &= 0 \end{aligned} \right\} \quad (7)$$

Formulas for Fault Currents and Voltages

LINE-TO-NEUTRAL SHORT CIRCUIT: A-N

If the load in Figure 6 is treated as a short circuit, the entire phase voltage E_{NA} is then consumed by the total impedance drop in phase A. Hence

$$E_{NA} = I_1 Z_1 + I_2 Z_2 + I_3 Z_3 + I_0 Z_0$$

If the values of I_1 , and so forth, are substituted from equation 5,

$$E_{NA} = I_A (Z_1 + Z_2 + Z_3 + Z_0) / 4 \quad (8)$$

As I_A is now I_{fault} , therefore

$$I_{\text{fault}} = 4E_{NA} / (Z_1 + Z_2 + Z_3 + Z_0) \quad (9a)$$

and for static circuits

$$= 4E_{NA} / (2Z_1 + Z_2 + Z_0) \quad (9b)$$

If the fault has an impedance Z_f , an impedance Z_f may be assumed in series with each one of the open lines also for symmetry, in which case each one of the impedances $Z_1, \dots, Z_0$ will be increased

by Z_f , changing equation 9a into equation 10

$$I_f = 4E_{NA} / (Z_1 + Z_2 + Z_3 + Z_0 + 4Z_f) \quad (10)$$

Another way of considering the fault impedance in this case is as one connected in series with the neutral, carrying a current $4I_0$, in which case, Z_1, Z_2, Z_3 are not affected, but Z_0 is increased by $4Z_f$, leading again to equation 10.

This equation 10 may be compared with that of the three-phase case, namely

$$I_{\text{fault}} = 3E_{NA} / (Z_1 + Z_2 + Z_0 + 3Z_f) \text{ in conventional notation} \quad (11)$$

The equivalent-sequence network of the four-phase circuit under consideration is shown in Figure 9. It follows from equations 9 and 10.

If we apply normal phase voltage (line-to-neutral) to this network, the resulting current is one of the sequence currents (all alike in phase A); if we apply four times that voltage, the resulting current is the fault current.

Equations 9 and 10 hold equally in absolute values or in per unit values, also in percentage values, in which latter case, however, the fault current is in terms of "times normal."

To illustrate the calculation of the terminal voltages under fault condition, V_{NB} will be seen to be given by equation 12 as the open-circuit voltage minus the four impedance voltages of phase B

$$\vec{V}_{NB} = \vec{E}_{NB} - (I_1 / 90^\circ Z_1 + I_2 / 180^\circ Z_2 + I_3 / 270^\circ Z_3 + I_0 / 360^\circ Z_0) \quad (12)$$

LINE-TO-ADJACENT-LINE SHORT CIRCUIT: A-B

In the light of Figure 7, if the load is treated as a short circuit, it will be seen that the open-circuit voltage E_{BA} is consumed by the impedance voltage in phase A minus the impedance voltage in phase B. And as E_{BA} is equal to $\sqrt{2} E_{NA} / 45^\circ$, therefore

$$\begin{aligned} E_{BA} &= (I_1 Z_1 + I_2 Z_2 + I_3 Z_3 + I_0 Z_0) - \\ &\quad (I_1 Z_1 / 90^\circ + I_2 Z_2 / 180^\circ + I_3 Z_3 / 270^\circ + I_0 Z_0 / 360^\circ) \\ &= \sqrt{2} I_1 Z_1 / 45^\circ + 2 I_2 Z_2 + \sqrt{2} I_3 Z_3 / 45^\circ + 0 \quad (13) \end{aligned}$$

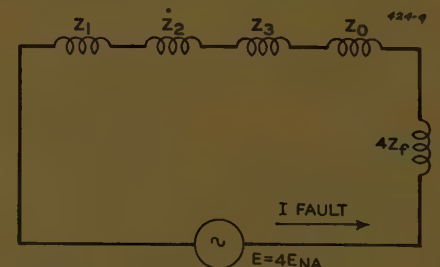


Figure 9. Equivalent sequence network of Figure 6

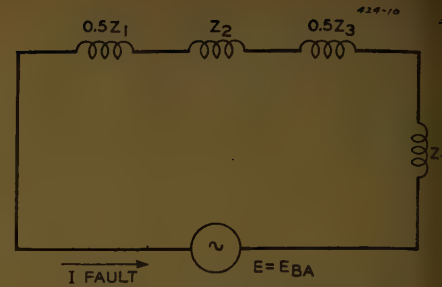


Figure 10. Equivalent sequence network of Figure 7

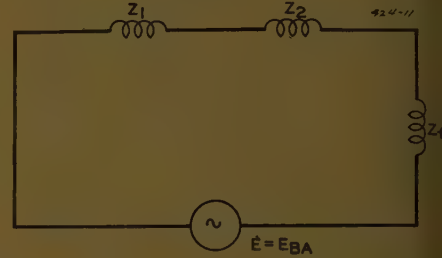


Figure 11. Equivalent sequence network of Figure 7 for static circuits only

If the values of $I_1, \dots, I_0$ are substituted from equation 6

$$E_{BA} = I_A (0.5 Z_1 + Z_2 + 0.5 Z_3) \quad (14)$$

Hence

$$\begin{aligned} I_{\text{fault}} &= E_{BA} / (0.5 Z_1 + Z_2 + 0.5 Z_3) \\ &= E_{BA} / (Z_1 + Z_2) \text{ for static circuits} \end{aligned} \quad (15a, 15b)$$

If the fault itself has the impedance Z_f , half of it may be assumed as in series with line A, the other half in series with line B; and for the sake of symmetry, a $Z_f/2$ may be assumed as existing also in series with each one of the open lines C and D, so that each one of the four sequence impedances $Z_1, \dots, Z_0$ is increased by $Z_f/2$, and formulas 15 are transformed to 16.

$$\begin{aligned} I_{\text{fault}} &= E_{BA} / (0.5 Z_1 + Z_2 + 0.5 Z_3 + Z_f) \\ &= E_{BA} / (Z_1 + Z_2 + Z_f) \text{ for static circuits} \end{aligned} \quad (16a, 16b)$$

Z_f could have been inserted in equation 16 by inspection, without reference to symmetrical components, but the reasoning in the preceding paragraph is given to illustrate a principle and method.

The sequence network of this is shown in Figure 10 (and 11), except that

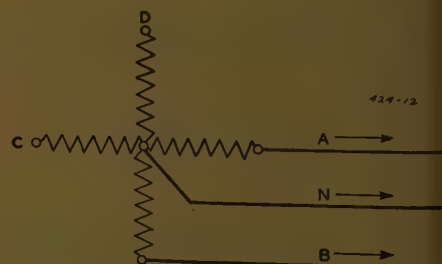


Figure 12. A quadrant short circuit

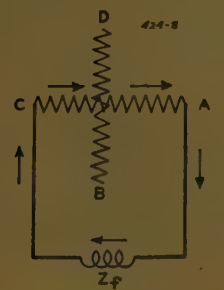


Figure 8. Single-phase load, across opposite lines

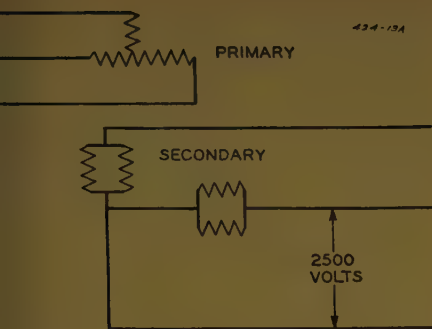


Figure 13A. Three-phase to quarter-phase connected transformer bank

represents only I_f or I_2 properly— I_f if E_{BA} is impressed, I_2 if half that voltage is impressed—but not I_1 or I_3 , as a consideration of equation 6 will make clear. Sequence networks may have such limitations.

If the resultant voltages under the fault conditions are required, the same reasoning as in equation 12 applies to the neutral-to-line voltages; and the line-to-line voltages follow from neutral-to-line voltages as in

$$\vec{V}_{CB} = \vec{V}_{NB} - \vec{V}_{NC} \quad (16c)$$

LINE-TO-OPPOSITE-LINE SHORT CIRCUIT: A-C

In the light of Figure 8 and equations 7

$$E_{NA} = I_1 Z_1 + I_2 Z_2 + I_3 Z_3 + I_0 Z_0 \quad (17)$$

$$= 0.5 I_A (Z_1 + Z_3) \quad (18a)$$

$$I_{\text{fault}} = 2 E_{NA} / (Z_1 + Z_3) \quad (18b)$$

The last is an obvious result, though not equation 18a.

The sequence network is evident from equation 18a.

A QUADRANT SHORT CIRCUIT: A-B-N

Case 2, involving lines A and B, did not involve the neutral, but, in this case, lines A and B are short-circuited to the neutral (Figure 12). Now there are three different fault currents: I_A , I_B , I_N . As I_N is the (negative) vector sum of I_A and I_B , and as I_A and I_B (as well as I_C and I_D) are the resultants of the sequence currents, the independent unknowns may still be taken as $I_1, \dots, I_0$, and the equations defining them are

$$\left. \begin{aligned} E_{NA} &= I_1 Z_1 + I_2 Z_2 + I_3 Z_3 + I_0 Z_0 & (a) \\ E_{NB} &= I_1 Z_1 / 90^\circ - I_2 Z_2 + I_3 Z_3 / 270^\circ + I_0 Z_0 & (b) \\ I_C &= 0 = I_1 \sqrt{180^\circ} + I_2 + I_3 / 180^\circ + I_0 & (c) \\ I_D &= 0 = I_1 / 90^\circ - I_2 + I_3 / 90^\circ + I_0 & (d) \end{aligned} \right\} \quad (19)$$

These can be solved perhaps more easily numerically, substituting the values of the impedances, the two known currents (0), and the two known voltages (1 or 100 per cent).

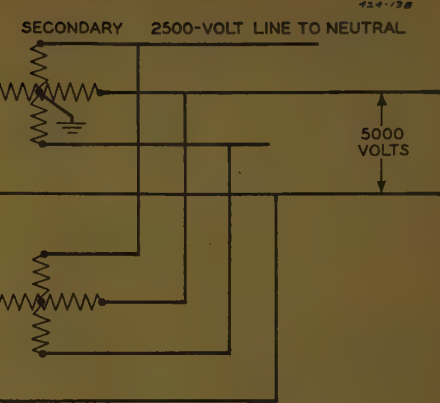
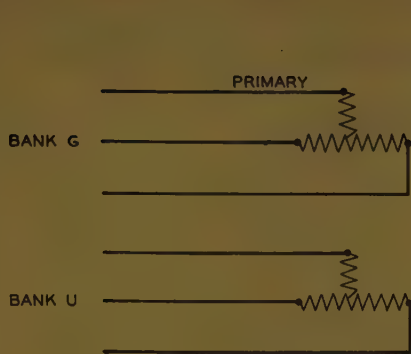


Figure 13B. Two banks of transformers in three-phase to four-phase connection

Bank G neutral-grounded; U ungrounded

The foregoing cases will illustrate how to proceed in the solution of other combination short circuits. Generally, the sum of the known voltages (consumed) and the known currents (zero) will be four, the same as the number of the unknowns, $I_1, \dots, I_0$, and therefore sufficient to solve the problem.

Example

Each one of two banks of three-phase to two-phase transformers is connected up as in Figure 13a. The secondary (two-phase) windings of each single-phase transformer are seen to be two in parallel, connected up for 2,500 volts. We wish to investigate the characteristics of the system if the two-phase coils are connected up in series for 5,000 volts and arranged four phase (Figure 13b) with the neutral of only one bank (G) grounded, the other (U) ungrounded.

The impedance data are as shown in Table I. The high value of Z_2 for the transformers arises from the fact that originally no loading of the mid-point of the secondary windings in 5,000-volt connection was contemplated, and therefore no provision was made to interlace the two halves. No values are entered for Z_2 for the primary lines because there is no current in them corresponding to I_2 in the secondary lines. For bank G, Z_0 is entered as equal to Z_2 , while for bank U it is entered as infinity because the neutral of this bank is ungrounded. While, in the design of the transformers, Z_2 and Z_0 are alike, yet in the system as a whole (last column) Z_0 has double the value of Z_2 on account of the particular neutral treatment—one bank neutral-grounded, the other bank neutral-isolated. These figures are all reactance values, the resistance components being ignored here as relatively small.

Currents

The value of the single-phase fault current, from one line to neutral, by

equation 9 will be seen to be

$$\begin{aligned} I_{\text{fault}} &= 4 \times 100 / (8.8 + 75 + 8.8 + 150) \\ &= 400 / 243 \\ &= 1.65 \text{ times normal, based on 15,000 kva} \end{aligned}$$

The components I_1 , I_2 , and I_3 divide equally between the two banks, but I_0 flows exclusively in bank A (with grounded neutral). As all components are equal in the fault, the current in the faulty phases (A) of the two banks will be

$$\begin{aligned} \text{Bank G, } I_A &= 2(5/8) 1.65 \text{ times transformer rating} \\ &= 2.06 \text{ times transformer rating} \\ \text{Bank U, } I_A &= 2(3/8) 1.65 \text{ times transformer rating} \\ &= 1.24 \end{aligned}$$

Voltages

The important question about the voltages is particularly the drops through the large Z_2 and Z_0 . A view of all four sequence drops is given in Table II.

In item 5 the negative voltage drop of 85.7 per cent means that, under the fault, the voltage of phase C rises to 185.7 per cent. Evidently this implies supersaturation of the core leg of phase C in bank G.

The voltages of the other phases of this or of the other bank can be similarly calculated (remembering that I_0 is zero for bank U).

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Modern Electric Locomotives in Open-Pit Mine Haulage

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EARLY in 1942 Phelps Dodge Corporation started production of copper from their new open-pit mine and reduction plant at Morenci, Ariz. One of the earliest mining districts of the state, Morenci had produced some 900,000 tons of copper since the beginning of operations in the early 70's, largely from ores of two to three per cent copper content, mined underground.

The ore body now opened had been explored from the earlier underground workings, and by churn and diamond drilling. It is estimated to contain 230,000,000 tons of ore averaging slightly over one per cent copper, capable of profitable recovery by open-pit mining, concentration, and smelting. The new operation, therefore, will produce more than twice the amount of copper previously taken from the district. In the extraction of this ore, approximately an equal amount of barren capping and slightly mineralized rock throughout the ore body will have to be removed and hauled to lean-ore dumps or to waste dumps in canyons adjacent to the mine.

Preliminary development to uncover sufficient ore and prepare the mine for the planned initial production of 25,000 tons of ore a day was started in 1937. This preparatory development included the removal of some 50,000,000 tons of material, establishment of benches in the mine area, construction of truck haulage roads and standard-gauge railroad for ore and waste haulage. In the first stages this work was handled mainly with 4 4¹/₂-yard full-revolving electric shovels and 18 22¹/₂-yard end-dump trucks. Later, with the formation of benches and construction of roadbed, rail was laid in the mine, and the main-ore and waste haulage tracks were installed, permitting the work to be taken over largely by trains of 30-yard side-dump cars. Four 125-ton Diesel-electric locomotives with engines of 1,000 horsepower sea-level rating, were put on trial

and used in this service, and in the latter stages the 125-ton electric locomotives that had been selected for main-ore haulage were utilized.

In the initial development, 11 mining benches were opened in the ore body, at a uniform height of 50 feet and average width of 100 feet, laid out at even elevations above sea level, the lowest at 4,750 feet and the highest at 5,250 feet. Benches vary in length up to approximately 4,000 feet. Ultimately the pit will be developed to a maximum length of 5,800 feet and will cover 350 acres. The lowest level to be worked will be the 4,200 and the highest the 5,500.

The nearest suitable location for the reduction plant in the rugged terrain of the district was a comparatively level section southeast of the mine. At this site the ore haulage tracks at the primary crusher were established at an elevation of 4,480 feet. From the nearest point of exit from the mine to the crusher the straight-line distance is about 1.8 miles, but the high hills and the town of Morenci lying between these points necessitated a considerably greater length of ore haulage track.

In the early part of the development period, analyses were made of the costs of ore and waste haulage for the planned maximum production of 40,000 tons of ore a day, based on operation on maximum grades of 3.4, 4 or 6.5 per cent. With the decision to limit the maximum grade to four per cent, construction of the track roadbed from the mine to the crusher was started.

The plan of ore and waste haulage tracks at the start of production was approximately as shown by Figure 1; some alterations have since been made. A series of switchbacks on a descending grade of four per cent, compensated for curvature, lead from the mine for nearly two miles to a section of 0.4 per cent descending grade a little less than a mile in length, terminating in a 0.4-mile level-approach track to the primary crusher. Successive mining benches are connected at the ends nearest the ore haulage tracks by switchbacks on four per cent grade. From the opposite ends of the benches tracks on maximum grade of 3.5 per cent

lead to approach tracks to four waste dumps in Coronado Canyon and one in Fairbanks Gulch, adjoining the pit. Dump tracks are on 0.25 per cent grade at elevations of 4,800 to 5,200 feet. Something over half of the total waste rock disposal during the life of the mine will be in Coronado Canyon, about 13 per cent in Fairbanks Gulch, and the remainder in Chase Creek Canyon, along the main-ore haulageway. Although the track elevation at the crusher, 4,480 feet, is about midway between the present and the final lowest mining bench, 4,750 feet and 4,200 feet respectively, it is estimated that 85 per cent of all material will be hauled over favorable grades.

Main-ore haulage tracks are laid with 131-pound rail, standard-gauge; bench and waste-dump tracks with 90-pound rail. Double track provided on the main-ore haulage road and passing tracks are not shown in Figure 1.

Comparisons were made of the amount of equipment required and the operating costs for ore haulage with solid-body or side-dump cars of different capacities,

Table I. Ore-Haulage Schedule for Locomotives in Continuous Operation Between Mining Bench (4,950 Feet) and Crusher

Number of cars in train.....	11
Weight of empty car.....	38.5 tons
Weight of ore load in car.....	90 tons
Running time with loaded train, down hill, from end of temporary track on 4,950-foot bench to crusher.....	31 minutes
Running time with empty train uphill, from crusher to start of temporary track on 4,950-foot bench.....	24 minutes
Delay of one minute at each of 4 switchbacks in each direction.....	8 minutes
Assuming locomotive switches to empty train at crusher and to loaded train at bench:	
Switching time at crusher.....	2 minutes
Switching time at bench.....	2 minutes
Total time of round trip.....	67 minutes

and with trains of different numbers of cars. These analyses were based on hauling 25,000 tons of ore in two eight-hour shifts, at the maximum train speeds considered permissible on the several sections of permanent, semipermanent, and temporary track, on an expected maximum average loading capacity of 6,050 tons in eight hours by each 4¹/₂-cubic-yard electric shovel, and at a maximum dumping rate of 3,400 tons per hour at the primary crusher. Although they indicated a greater investment for equipment and higher energy consumption with side-dump cars in ore haulage, there were compensating advantages in simplification of mine operation and train dispatching by the use of cars of the same type in both ore and waste-haulage service, and in elimination of the large ca-

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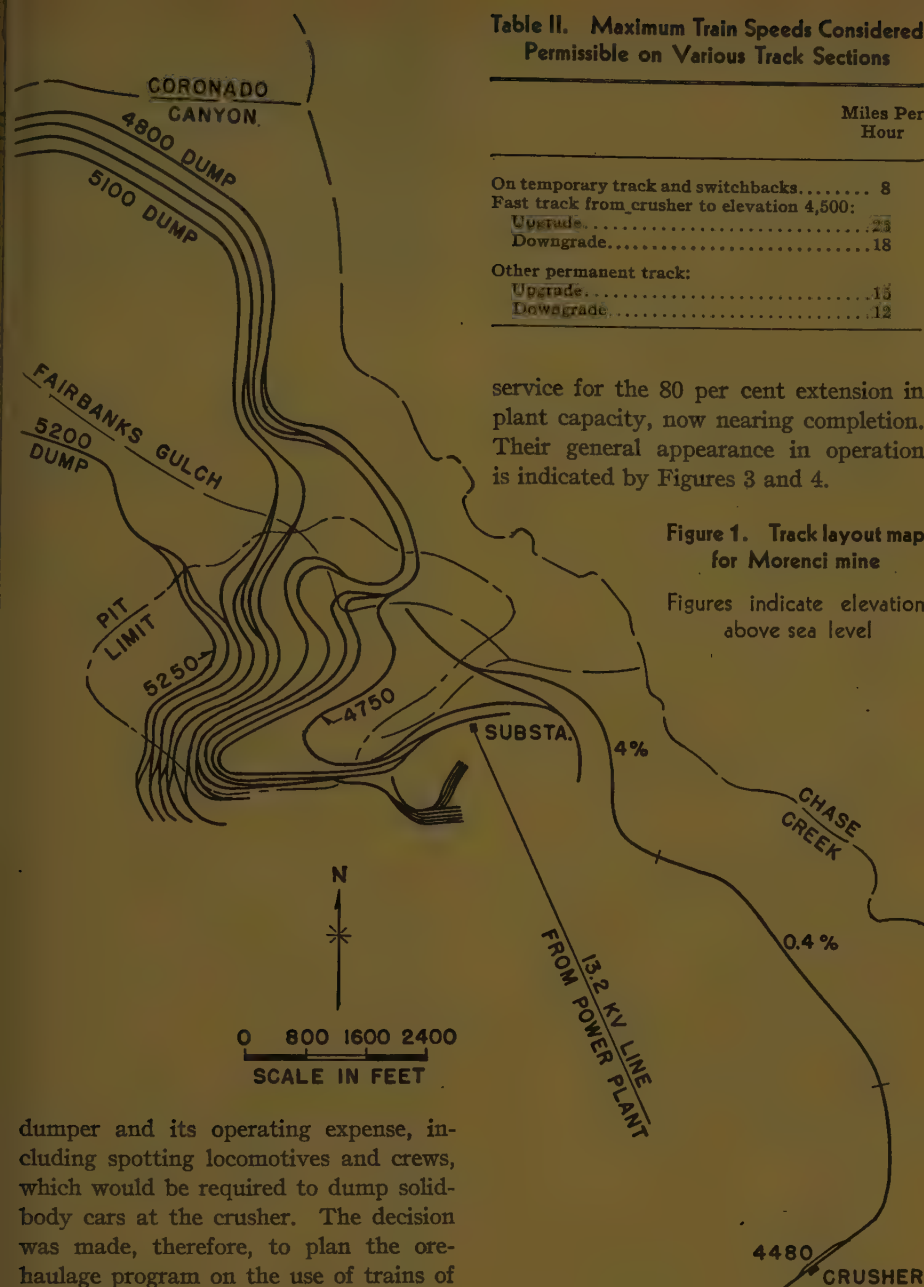
Table II. Maximum Train Speeds Considered Permissible on Various Track Sections

	Miles Per Hour
On temporary track and switchbacks.....	8
Fast track from crusher to elevation 4,500:	
Upgrade.....	23
Downgrade.....	18
Other permanent track:	
Upgrade.....	15
Downgrade.....	12

service for the 80 per cent extension in plant capacity, now nearing completion. Their general appearance in operation is indicated by Figures 3 and 4.

Figure 1. Track layout map for Morenci mine

Figures indicate elevation above sea level



cars in use have an empty weight of approximately 45 tons and carry from 90 to 100 tons of ore or waste.

To insure adequate capacity for the most severe duty that might be imposed in haulage service co-ordinated with the maximum rates of loading by $4\frac{1}{2}$ -cubic yard electric shovels and dumping at the primary crusher, the locomotives are capable of maintaining continuous operation between the mining bench at 4,950 feet elevation and the crusher on the ore-haulage schedule shown in Table I.

The maximum train speeds considered permissible on various track sections are shown in Table II.

BENCH OPERATION

Although it is practicable to operate electric locomotives from temporary trolley structures on the mining benches, in order to free operations of any impediment from such structures in the mining areas and to avoid the delay and expense of maintaining and moving them in the progress of mining, it was deemed advisable to make other provision for train movements on bench track. Alternative arrangements considered were:

(a). Cable reel on the locomotive for power supply on bench tracks beyond the ends of electrified sections. Such operation was somewhat dubious because of the great lengths to which the mine benches will extend, the slow speeds necessary when operating on cable reel paid out from the locomotive, and the probability of rapid wear and short life of cable in such service.

(b). Auxiliary Diesel-engine-generator set on the locomotive to supply power for train movements on unelectrified bench tracks. Because of the increased cost of an auxiliary unit of sufficient power for satisfactory movement of loaded and empty trains on bench tracks, and the operating complications which would be introduced, this arrangement was concluded to be undesirable.

(c). A storage battery on the locomotive of sufficient capacity for train movements at the desired speeds on the benches was decided to be worthy of trial.

Each locomotive is equipped with a storage battery applied for an expected life of approximately five years. The most severe duty cycle on the battery for train movements on benches was estimated to be for power supply in the following operations:

Hauling a train of 11 empty cars from the start of temporary track on the 4,950 foot bench to the far end, a distance of 4,000 feet, in approximately $5\frac{1}{2}$ minutes.

Spotting 11 cars at the shovel for loading at the rate of 15.75 tons per minute.

Accelerating the train of 11 loaded cars at a maximum rate of 0.1 mile per hour per

OPERATING VOLTAGE

The locomotives are designed for operation at a nominal-contact trolley-line voltage of 750 volts direct current and a maximum voltage of 900 volts at no load in the mercury-arc-rectifier substations supplying the trolley circuit.

LOCOMOTIVE WEIGHT AND HAULAGE CAPACITY

The locomotive weight of 125 tons was selected to permit hauling the maximum train of 11 38.5-ton empty cars up the four per cent grades with an estimated adhesion of slightly over 19 per cent, and to provide by electric braking over 40 per cent of the retarding effort required with trains of 11 128.5-ton loaded cars descending the four per cent grades. The

dumper and its operating expense, including spotting locomotives and crews, which would be required to dump solid-body cars at the crusher. The decision was made, therefore, to plan the ore-haulage program on the use of trains of 11 side-dump cars of 40 cubic yards capacity each.

Analyses were made also of the initial investments, operating costs and other features of ore and waste haulage with:

(a). Diesel-electric locomotives.

(b). Electric locomotives for operation from a 750-volt trolley circuit, using power from the projected 50,000-kw turbine generating plant at the reduction works. Previous estimates on a 1500-volt system had shown no advantage over 750 volts in this service and had confined further considerations to the lower voltage.

Electric Locomotives

In the final analysis, electric locomotives were selected for main-ore and waste haulage at Morenci. Nine locomotives were placed in service during 1941 for the initial production of 25,000 tons of ore a day, and seven more are in

second and hauling it back to the trolley at the start of permanent track in approximately 6½ minutes.

Operating air compressor for braking service, and supplying lighting, heating, and control circuits.

The 240-cell 500-volt lead-acid storage battery applied to each locomotive has a discharge capacity of 500 ampere-hours on a six-hour basis, approximately 70 per cent of the estimated output required for six complete bench cycles in average duty. The complete battery weighs approximately 14 tons.

A large part of the battery output in each bench cycle is restored during the succeeding interval of time in which the locomotive is operating under the trolley to the crusher with loaded train, while dumping cars and when returning the empty train to a mine bench. Automatic charging equipment on the locomotive connects the battery to the trolley circuit through suitable resistors, providing at the start a high charging rate and later a reduced rate when the battery charge has been restored to a predetermined value.

With the locomotives in service for three eight-hour shifts each day, the batteries automatically are returned to full charge during the runs to and from the crusher. Under other conditions, such as waste-haulage and dump operation, occasional lay-up for recharging is necessary. Periodic equalizing charging is also regular practice. A lay-up track is provided at the mine pit shops for recharging from the trolley wire, and the batteries automatically are disconnected at full charge. Daily gravity readings are taken to check battery conditions.

As it is expected that, after some years of further development of the mine, the frequency of movement of bench tracks will be less than that necessary in present operation, and it later may become advantageous to operate from portable

trolley over the bench tracks, all locomotives are arranged for the addition of side-arm collectors, when desired.

ELECTRIC BRAKING

Studies were made of the merits of regenerative braking or dynamic braking on the locomotives to assist the straight or automatic air brakes in retarding loaded trains on descending grades, and thereby reduce wheel and brake-shoe wear and maintenance and replacement costs. The decision to adopt dynamic braking was based mainly on the lower cost and relative simplicity of locomotive and substation equipment.

The dynamic brake on each locomotive is capable of producing retarding efforts up to 50,000 pounds at train speeds between 8 and 18 miles per hour.

Construction of Locomotives

Haulage conditions encountered in a project such as the Morenci mine have led to the development of a locomotive specially adapted to this duty. Figure 5 shows the general dimensions and construction.

The running gear consists of two four-wheeled trucks, having welded steel frames supported by a combination of coil and half elliptic side springs. The trucks are permanently coupled together with aallet or ball hinge, and the drawheads are built into the truck bumpers, so that all draft and bumping stresses are continuous throughout the running gear and are not in any way transmitted to the cab structure. Articulated trucks are particularly suited to the severe duty on rough track, grades, and curves, and do not swing crosswise to the track in case of derailments.

The cab has a rigid underframe which is supported on two center pins located in the middle of the truck bolsters. Side-spring restraining plungers carry a portion of the cab weight on the inner truck bumpers. One center pin is provided with longitudinal motion to compensate for the

changing center distances on curves. Normal design for a locomotive of this length and type would weigh considerably less than 125 tons. The additional ballast required by the starting conditions has been built into the structural members and provides a large margin of mechanical strength. A novel structural feature is the use of heavy end plates and rock guards which protect the motors, journal boxes, and steps from damage by loose rock and other track obstructions. Clearance below the rock guards is one inch less than the motor clearance.

To provide maximum visibility for the operator, cabs are of the steeple type, with sloping hoods at each end, and an elevated operating compartment in the center. In addition to the control compartment, there are five apparatus compartments, two at the ends for the battery, two adjacent equipment compartments, and a central resistor space under the operating deck.

Each of the two equipment compartments includes a blower for two traction motors and an air compressor, one for the air brakes and one for the car-dumping system. Electrical control apparatus for operation of the traction motors and auxiliaries is also housed in this space. Ventilating air is drawn in through air filters in the side walls and delivered to the traction motors through the hollow center bearings.

The control station is so located that the operator has full vision in all directions and by means of mirrors can see the blind side of the train. A double-shoe pantograph trolley is mounted on the roof of the operating compartment.

PERFORMANCE

Under present operating conditions, a typical round-trip run between loading benches and the crusher is nine miles, with 470 feet change in elevation and

Figure 2. General view of the mine pit and benches, showing progress made early in 1943



Figure 3. Electric locomotive spotting ore cars for loading at a bench shovel



Figure 4. Locomotive and train unloading waste

switchbacks involving four stops and reversals in each direction. The maximum round-trip run is 15 miles, with 770 feet change in elevation and several additional switchbacks. Numerous, four per cent grades averaging 1,300 feet in length on switchbacks are with the load, which means that upgrade operation with the empty train is an important factor in determining locomotive capacity and schedule speeds.

The average round trip from bench to crusher requires about one hour, to which must be added a 1- to 1½-hour loading period on the bench. Under ideal scheduling of operation, nine round trips will move 7,000 to 8,000 tons of ore in 24 hours.

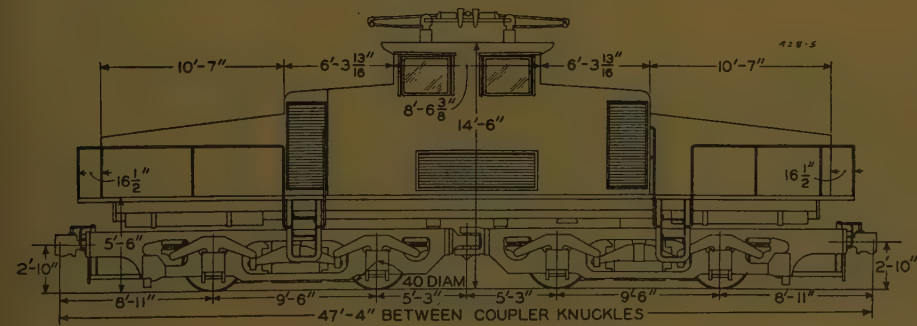
Train lengths are adapted to the length of tail tracks at the switchbacks. Normally, trains are made up of nine 45-ton dump cars, each of which will hold 90 to 100 tons of ore, making a trailing load of 405 tons upgrade, and 1,200-1,300 tons downgrade. Safe downgrade speeds with full load are limited by curves and track conditions to from 12 to 18 miles per hour. Return speeds with empties are from 15 to 25 miles per hour, depending on the grade.

Speed and tractive-effort characteristics of the locomotive are shown in curve data form by Figure 6.

MOTOR CONTROL

Because of the great variety of starting and running conditions, the three-speed

Figure 5. Sideview and general dimensions of 125-ton electric locomotive



system of motor control is used, involving series, series-parallel, and parallel connections for the four motors. The one-quarter and one-half speed connections are particularly useful in battery operation where economy of ampere-hours is important. Spotting of cars at the shovels and crusher also makes use of the low-speed notches.

There are a total of 22 starting notches, an ample number for starting a loaded train on grades and curves, without wheel slippage. Sand is used when rail conditions are abnormal. All motor combinations and resistor switching are managed with remotely controlled electropneumatic switches. The motors are also switched from line to battery power with an electropneumatic transfer switch. The controls for all motor and auxiliary operations are centrally located so that the operator has full charge of the entire locomotive without moving from the control platform.

Figure 7 shows the distribution of the starting notches in terms of speed and load, and also the dynamic-braking notches which control retardation. Maximum current for acceleration can be held at 500 amperes per motor, and for braking 400 amperes per motor. Motor currents are indicated on cab ammeters at all times.

In the interest of simplicity and economy of space, the traction motor switching and resistor equipment are arranged for the double purpose of starting and dynamic braking. The additional equipment necessary for braking is thus held to a minimum.

Figures 8, 9, 10, and 11 illustrate the switching circuit combinations used for series, series-parallel, parallel, and dynamic braking.

As the master controller is moved from the 8th to the 9th, and from the 15th to the 16th notches, the motors are reconnected in the different combinations, resulting in higher voltage per motor and higher speed. The process of reconnecting the motors is known as transition. In the ninth notch, the motors of each truck are in series but the two trucks are

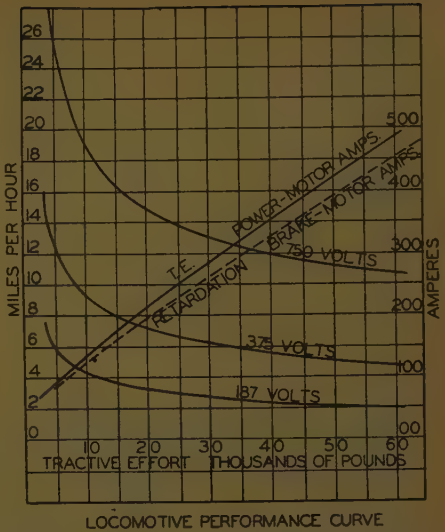


Figure 6. Locomotive performance and tractive-effort curve

now in parallel, giving one-half voltage to each motor and its series resistance. During the interim between the eighth and ninth notches, the motors of the number 2 truck are by-passed, giving a momentary loss of tractive effort. This is known as shunting transition.

Between the 15th and 16th notches, the motors in the two trucks are reconnected in parallel, giving full voltage per motor circuit. The change in this case is made by the bridge method wherein the transition is set up by paralleling the two motor circuits without interrupting the flow of current in either motor and, consequently, without loss of tractive effort.

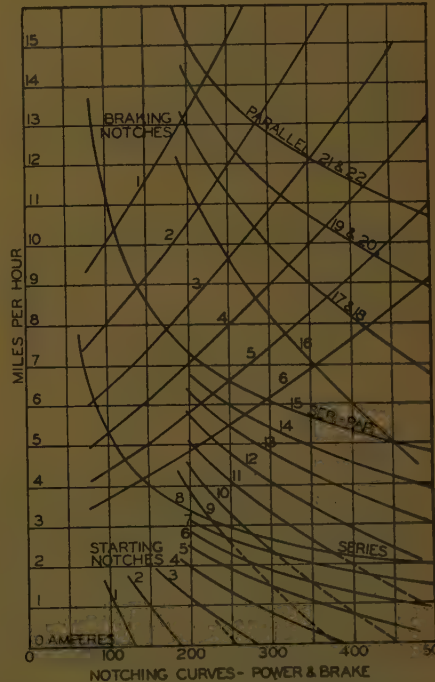


Figure 7. Power and brake-notching curves showing uniformity of current regulation

Obviously, the control of braking speeds with loaded trains on four per cent downgrades is an important feature of safe operation. Three braking systems are provided, the standard automatic air brake, a separate straight air nonautomatic train brake, and the dynamic brake.

The total braking effort necessary to hold a loaded train on four per cent grade is approximately 100,000 pounds which, if developed entirely by the brake shoes, would result in overheating and rapid wear of shoes and wheels, with frequent replacements and excess maintenance.

The dynamic brake, which is a generating action developed by the traction motors, is designed to supply approximately one half of the total retardation needed, or about 50,000 pounds. This relief of brake-shoe duty more than doubles the life of brake shoes, reduces the frequency of flat wheels, and provides an important safety factor in the handling of trains.

Series traction motors can be made to

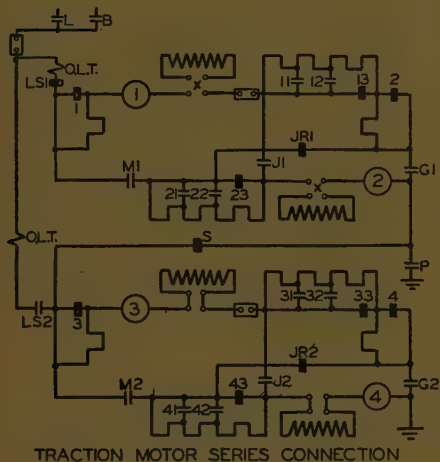


Figure 8. Motor-control schematic diagram showing series connection for slow-speed operation

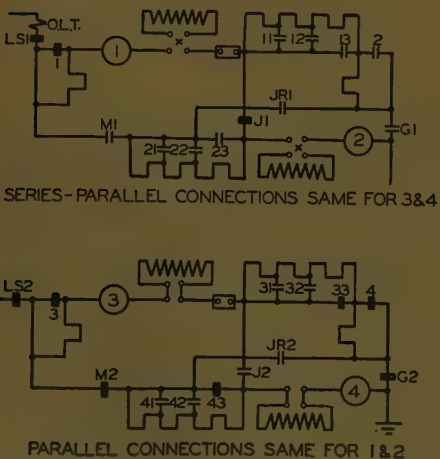


Figure 9. Schematic diagram for series-parallel and parallel connections

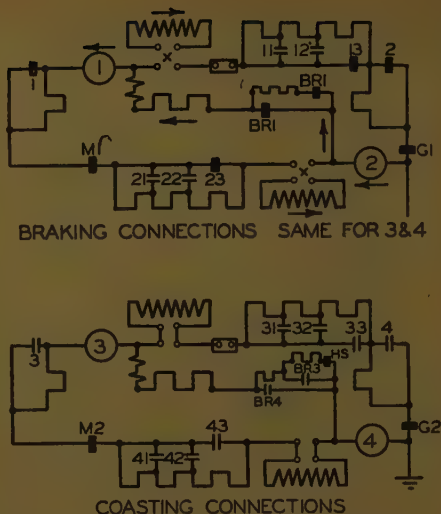


Figure 10. Schematic diagram of coasting and dynamic-braking connections

act as generators, and, when so doing, their torque is reversed, and they produce a braking action. This action, known as dynamic braking, is used to supplement the air braking to hold trains at constant speed on downgrades. The electrical output of the generators is absorbed by resistors.

If a series motor is driven from some mechanical source of power (as a locomotive axle) and a resistor is connected across its terminals, it will not build up to act as a generator because of improper direction of current in the series field. However, by using a pair of motors and connecting the resistor from a point between the armature and field of one motor to a corresponding point of the other motor, as shown by the circuit through the BR switch on the main schematic, the armature of one motor feeds the field of the other, and braking is obtained.

Each pair of motors, therefore, acts as a dynamic-braking system feeding its output into the resistor through the BR switches. Advance of the braking control varies the amount of resistance in series with each motor and hence the speed at which full dynamic-braking effect is obtained.

A resistor is connected across the BR 3 switch and is brought in circuit by the HS contactor, which is closed whenever the controller is in the "off" position. Its purpose is to set up a high-resistance braking circuit during coasting. The amount of braking effort produced by this circuit is negligible, but the current flowing in the resistance serves to provide a voltage for actuating the overspeed relay. At speeds above approximately 18 miles per hour, the voltage across the resistance is sufficient to cause the relay to lift, and this prevents the establishment of the full braking circuits. It is, therefore, impossible to obtain dynamic braking at excessive speeds, which would generate abnormally high voltages.

The energy generated by retardation must be dissipated as heat in the resistors. This is also true of the starting losses. In the service described, all of the resistor load periods are of short duration, making an ideal application for grid resistors of large thermal capacity, with natural ventilation. A small amount of air is diverted from the motor blower system to supplement ventilation of the resistors and to continue the cooling process while the locomotive is standing.

To get the maximum benefits from the dynamic system in holding a constant speed on heavy grades, there must be facilities for building the dynamic retardation up to a predetermined amount and then supplementing this with suffi-

Figure 11. Sequence of switching applying to diagrams shown in Figures 8, 9, and 10

BRAKING		COAST		PARALLEL		SER.-PAR.				SERIES				NOTCHES																																			
5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50				



Figure 12. General view of a 750-volt 375-horsepower traction motor

roller-type armature bearings and oil and waste axle bearings. Labyrinths on the armature shaft and housing retain the grease for the roller bearings, so that greasing is needed only at infrequent intervals. The air intake for forced ventilation is cast into the frame at the rear and obtains air from a vertical opening in the truck bolster.

The inherent inductance of the motor is sufficient to smooth out ripples in the

the commutator. Field coils are seated between machined pads in the frame and spring washers under the pole tip. Coils are fitted tightly on the poles.

Commutating characteristics are such as to withstand the over-voltages encountered in dynamic-braking service and hold the volts per bar on the commutator within conservative limits. Armatures are dynamically balanced both before and after winding.



Figure 13. Operator's station, showing the arrangement of control, brake, and auxiliary levers

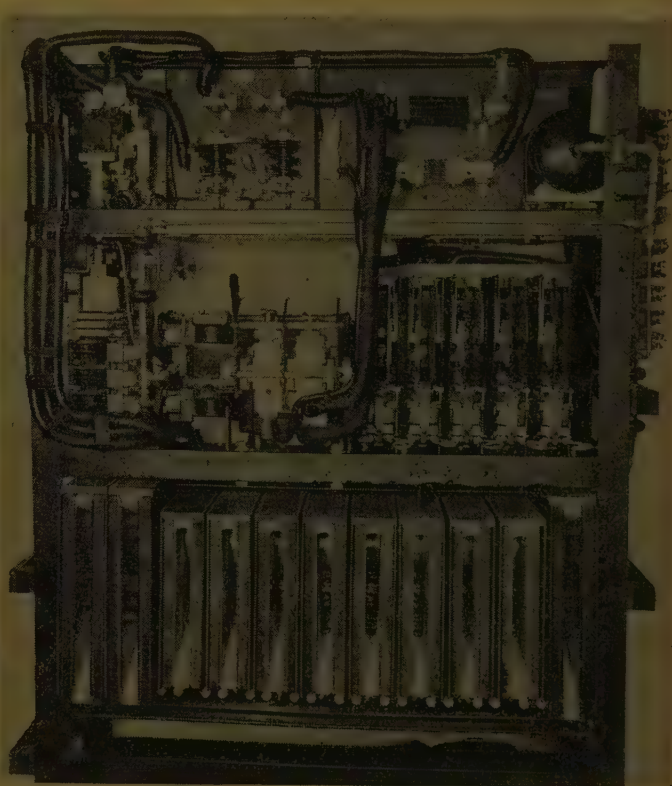


Figure 14 (right). Pre-assembled panel of motor-control apparatus

cient air braking to suit the load, grade, and the desired speed. In order to simplify the procedure of blending the two brakes, the dynamic load is regulated by series resistors to a constant value. Current-limit relays control the closing and opening of resistor switches to hold the braking effort between narrow limits over a speed range between 18 and 8 miles per hour. After the initial application, this regulation is automatic, leaving the operator free to give full attention to the manual graduation of the straight air train brake as needed to hold the desired speed.

MOTORS

Four 750-volt 340-horsepower axle-mounted traction motors drive the four axles through single-reduction spur gearing. Mechanical and electrical design features are especially suited to the type of service encountered in mine haulage.

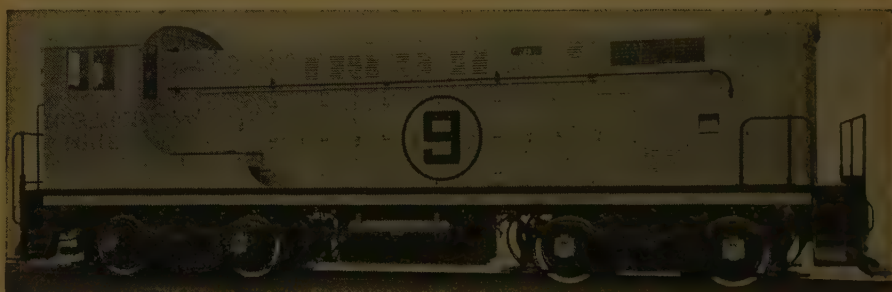
A general view of the traction motor appears in Figure 12, which shows the frame as a heavy steel casting, with

current supply. In addition, laminated commutating poles are used to reduce sparking at the commutator with sudden changes of current due to interruption and reapplication of power.

Armature and field coils are finished with class-B insulation, and the armature coils are heated and pressed before installation. After being connected, they are banded while hot, wedged with Micarta, and rebanded with nonmagnetic banding wire. These features reduce operating losses, improve the continuous rating, and reduce sparking volts at

Similar operating margins have been incorporated in the design of the blower and compressor motors. Each blower motor is rated ten horsepower at 400 volts and 2,100 rpm. The two are connected permanently in series, to take advantage of the resulting low-voltage commutator design. Compressors use direct drive from 25-horsepower, 800-rpm motors which are wound for full

Figure 15. A typical 1,000-horsepower 125-ton Diesel-electric locomotive



voltage and very generously proportioned to withstand the frequent starting service.

OPERATING EQUIPMENT

In arranging the operator's cab, particular attention has been given to convenience and visibility needed for frequent reversals of train movement. Figure 13 shows the arrangement which has proved to be most satisfactory.

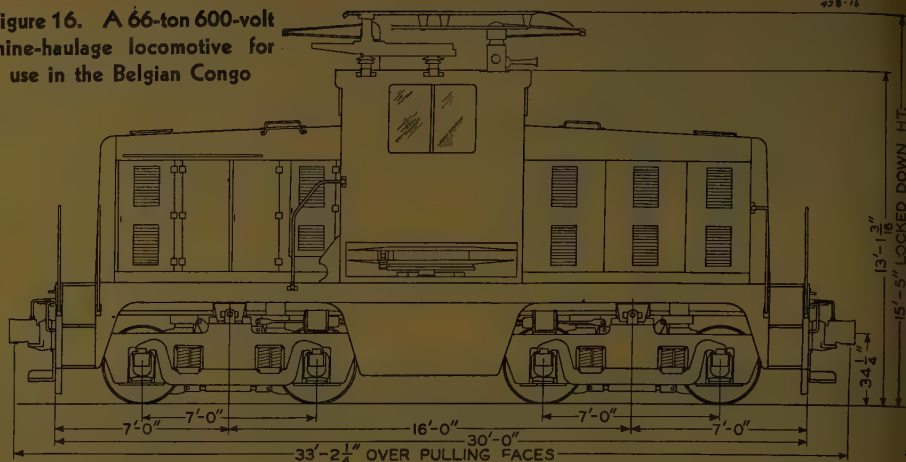
All normal starting and braking functions are controlled by means of conveniently located master control and brake handles as follows:

- 22-notch motor controller.
- Reversing-control lever.
- Motor cutout switch.
- Dynamic-brake master controller.
- Automatic air-brake valve.
- Independent locomotive brake lever.
- Straight air train-brake valve.
- Disconnect switch for auxiliaries.
- Miscellaneous auxiliary switches and push buttons.

Certain of the auxiliaries, such as lights and master-control supply are fed directly from the battery at all times. Other auxiliaries, such as blowers and compressors, are switched to line or battery by the main transfer switch which is thrown by the operator when passing to and from the trolley-wire sections.

For convenience in maintenance, as well as in original manufacture, the motor-control equipment has been mounted in preassembled racks, as shown in Figure 14. One of these assemblies is mounted in each of the two hood compartments, which are isolated completely from the operator's cab. All power-switching equipment is remotely controlled and is of the well-known electro-pneumatic type, particularly adapted to heavy duty. An important factor in service reliability is the use of 1,500-volt rated insulation for power apparatus.

Figure 16. A 66-ton 600-volt mine-haulage locomotive for use in the Belgian Congo



In constructing the second lot of Morenci locomotives, it has been possible to incorporate numerous details of arrangement for operating and maintenance convenience, based on experience in handling the original installation. The final design is, therefore, adapted to the operating conditions on this particular property and also establishes standards which can be applied universally wherever large quantities of material are to be handled. That these aims have been realized, is indicated by the high degree of locomotive availability which is being maintained at Morenci Mine.

Other Modern Haulage Locomotives

Figure 15 illustrates one of the 125-ton Diesel-electric locomotives used in waste haulage and for general duty at Morenci Mine. With skillful dispatching, it is practicable to make economical use of both types of motive power in the varied phases of haulage service.

Stripping operations at present require the removal of approximately equal amounts of ore and waste. The Diesel-

electric locomotives of 125 tons are used for a portion of the operation on the long dump tracks, which have light grades and no overhead wire. Line construction is being extended, with the addition of substation capacity, all pointing to the further general use of the electric locomotives.

The electric locomotive illustrated in Figure 16 is one of five 66-ton 42-inch gauge 600-volt units now under construction for use in open-pit copper mining in the Belgian Congo. The general characteristics are quite similar to those of the Morenci locomotives, with the exception that, instead, of a storage battery for bench operation, a cable reel and side-arm collectors are to be used. Short benches, and other differences in the mine layout indicate that a battery is not essential to satisfactory performance.

Maximum grades on this property are two per cent against the load. The empty train amounts to a trailing load of 220 tons, and the loaded train is 440 tons. These locomotives will handle all of the ore and waste haulage and will be subject to diversified grade conditions.

A New Electric Hoist Drive for Cranes

M. A. WHITING
ASSOCIATE AIEE

A NEW system of electric hoist drive has been developed, and its success has been demonstrated in practical use. For the types of hoist for which it is particularly intended this system provides a closer approach to the ideal characteristics than has previously been available. Although the system is not intended for use in all of the important types of hoist, it is expected that further experience and additional study of details and refinements will broaden its field of application beyond that which has, to date, been established in practice.

The Ideal Characteristics

Among the several hoisting applications for which the new system is believed to be suitable, the high-grade heavy-duty indoor cranes in steel mills and heavy machine shops may be considered typical. A study of the requirements indicates that the ideal characteristics for a crane of this type and of certain other types are principally as follows:

The same manipulation of the controller to any position in the lowering direction should cause the motor either to deliver power for lowering an empty hook or to absorb power for the proper lowering of a load, whichever is required by the conditions at that moment.

1. Maximum hoisting speed at empty hook should be a definite value, approximately twice the speed at rated load.

2. At the full-speed hoisting position of the controller the stalled torque should be limited to a reasonable overload value.

3. At the first-speed hoisting position the speed-torque curve should be relatively flat, having a very low speed at empty hook but a substantial stalled torque.

4. The maximum lowering speed at empty hook should be a definite selected value, between 160 per cent and twice rated hoisting speed.

5. Maximum speed of lowering rated load should be substantially less than at empty hook, and maximum speed of lowering maximum load should be less than that of lowering rated load.

7. The minimum lowering speeds, that is, the speeds at the first lowering-speed position of the controller should be nearly alike, irrespective of load. If readily attainable, it is preferable that this lowering speed be less at heavy loads than at partial loads or empty hook.

8. The electric equipment must have in the lowering direction a substantial margin, so that, when the maximum load which can be lifted is handled, the torque capacity available in the lowering direction is ample to maintain dependable control of the load under the most adverse conditions.

9. A safe and reasonably smooth retardation and stop must occur automatically in the event of failure of incoming power and other emergencies.

10. The regulating means by which the fifth, sixth, and seventh requirements are met must *not* be capable of stalling a load which is being lowered, however great that load may be, at any lowering position of the controller.

11. The electric equipment should be self-protective against abuse, either of itself or of the mechanical equipment, under the condition of rapid and unrestrained movement of the controller handle.

12. It is usually important that the holding brake be so controlled automatically that in regular service it is not required to supply any large part of the retardation effort.

The reasons for some of the items in this list of ideal requirement are probably evident. The reasons for some of the other items have been explained by J. A. Jackson.¹

Characteristics of Previous Systems

The most highly developed crane-hoist system using an a-c motor consists of a conventional wound-rotor induction motor and secondary resistance control with the addition of d-c dynamic braking in the lowering direction. The d-c dynamic braking is obtained by exciting the motor stator with direct current and absorbing in a controlled resistor the power regenerated by the rotor when lowering a load. This system has proved very useful, particularly in shipyard cranes. Figure 1 shows typical speed curves at the various controller positions plotted against load on the hook, at an assumed mechanical efficiency of 87 per cent. Certain additional speed-load characteristics, not shown in Figure 1, are provided solely as automatic transition points for acceleration and retardation. The examination

of Figure 1 shows that this system fulfills some of the ideal requirements stated in the introduction but departs considerably from this ideal in certain other respects.

For use with d-c power, the most highly developed crane-hoist-motor system commonly used is one in which the hoist motor is built as a series motor and is operated as a series motor in the hoisting direction. In the lowering direction a resistor of substantial capacity is connected to furnish a component of separate excitation to the series-wound field and to provide a dynamic-braking path for absorbing current regenerated by the armature when a load is being lowered. Several manufacturers build equipments of this type which are essentially similar but differ in some details, and whose characteristics are similar, with minor differences. This system has been in general and successful use for approximately 30 years and is a radical improvement over earlier practice. A typical set of speed-load characteristics is shown by Figure 2, which is a combination of Figures 5 and 6 of Jackson's paper.¹ A study of this figure shows that it meets or approximates some of the ideal characteristics set forth in the introduction but departs widely from this ideal in certain other respects.

That form of the Ward-Leonard system which uses a three-field "shovel-type" generator^{2,3} has occasionally been proposed for the type of hoist here considered. Although this has been the standard system for shovels and is an

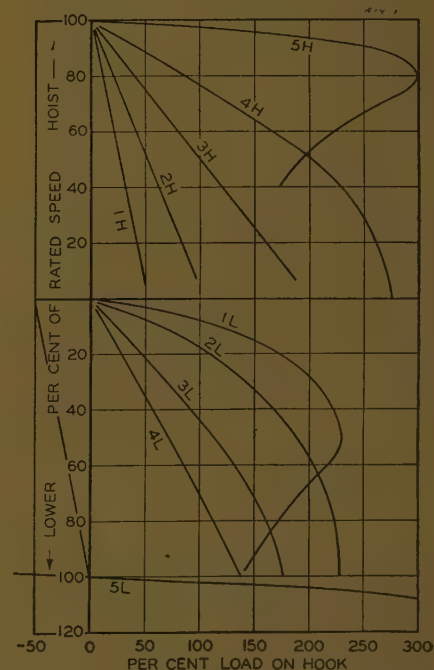


Figure 1. Characteristics of a-c crane hoist motor with d-c dynamic braking

¹ Paper 44-19, recommended by the AIEE committee on industrial power applications for presentation at the AIEE winter technical meeting, New York, N. Y., January 24-28, 1944. Manuscript submitted November 10, 1943; made available for printing November 30, 1943.

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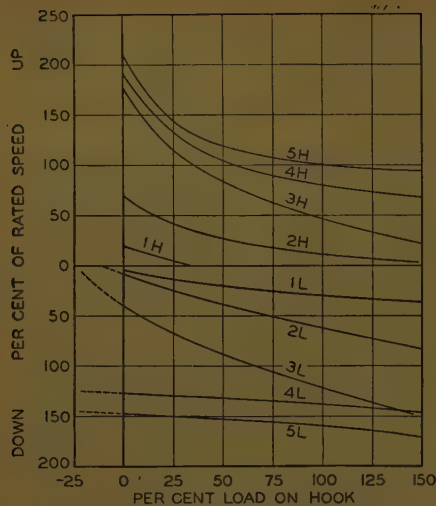


Figure 2. Characteristics of d-c series crane hoist motor with dynamic braking

excellent choice for certain other applications, its speed-torque curves differ widely from most of the ideal characteristics here considered.

The New System

The ideal characteristics for the applications under consideration have been approximated closely by the development of a radical improvement of the Ward-Leonard system, the principal feature of which is the addition of an exciter of unusual design embodying a cross-flux principle. By this means, a characteristic is obtained in which the voltage of this cross-flux exciter is responsive in a unique manner to the variations of magnitude and polarity of the current in the "loop" circuit, that is, the local circuit comprised by the armatures of the generator and hoist motor. At zero "loop" current the voltage of this exciter is at its maximum. At substantial increases of "loop" current, *irrespective of polarity*, the voltage of this exciter decreases, and at the maximum overload values of the "loop" current the voltage closely approaches zero. The voltage generated by this exciter provides the excitation of the generator field and modifies the excitation of the motor field. By means of the generator and motor-excitation characteristics thus provided, characteristics of speed versus load are obtained of the kind illustrated later in the paper (Figures 6 to 9).

The 9th and 12th requirements listed in the foregoing for the ideal crane hoist are met respectively by a simplified arrangement of an emergency dynamic-braking resistor in the hoist-motor armature circuit and by an improvement in the control details of the magnet brake. These two features are not de-

pendent upon the cross-flux-exciter principle. They were, however, developed as contributions to the same project, namely, the attempt to achieve the almost perfect crane-hoist drive. Because of lack of space, these features are not described.

Construction of the Exciter

Figure 3 illustrates diagrammatically the principles of construction of the cross-flux exciter in its basic form. Although multipolar machines are possible, the exciters built to date are bipolar, by which is meant that the armature-winding and commutator connections are those of a normal bipolar machine. Four pole pieces are provided. In Figure 3 the two upper pole pieces constitute one "pole" insofar as relates to the generation of the output voltage. The two lower pole pieces constitute the other "pole." For reasons which will appear, a degree of artificial saturation is introduced in the pole pieces, for example, by notches in the sides of the pole pieces as indicated in Figure 3. In one design which has been used, all pole pieces are duplicate (ordinary manufacturing variations being entirely acceptable). In another design which has also been used, the diametrically opposite pole pieces $P1$ are duplicates, each having a high degree of artificial saturation; the diametrically opposite pole pieces $P2$ are duplicates but have a much less degree of artificial saturation. For the general explanation, let all pole pieces and their respective air gaps be considered duplicate.

Each pole piece carries a shunt main-field winding separately excited from the constant-voltage main-excitation bus, also a cross-field winding consisting of a few turns of heavy conductor connected in series in the "loop" circuit, that is, in the main armature circuit of the Ward-Leonard system. Corresponding wind-

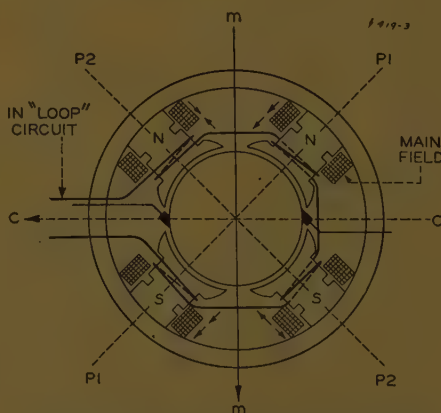


Figure 3. Diagrammatic representation of construction of cross-flux exciter

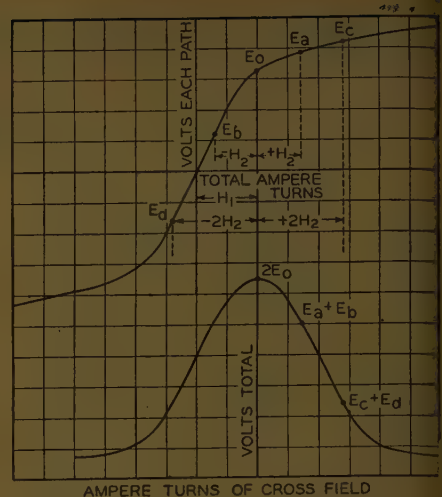


Figure 4. Theoretical characteristic of cross-flux exciter

ings ordinarily have equal numbers of turns upon all pole pieces. The polarity axis of the separately excited main field is shown by arrow $m-m$ in Figure 3. Stated in another way, when the sole excitation is by this main field the two upper pole pieces are of like polarity, for example "north," and the two lower pole pieces are of like polarity, "south." The polarity axis of the heavy cross field is in quadrature to that of the main field, that is to say, if the sole excitation were that of the cross field, the two right-hand pole pieces would be of the same polarity, for example "north" at the normal direction of "loop" current, and the two left-hand pole pieces correspondingly would be of "south" polarity. For the normal direction of "loop" current, the polarity axis of the cross field is shown by arrow $C-C$. As a result of this arrangement of coil polarities, at the normal direction of "loop" current, the respective field windings are of additive effect upon both pole pieces $P1$ but are opposed upon both pole pieces $P2$, as indicated by the small arrows located alongside the respective coils in Figure 3. The respective fluxes, although merged in parts of the magnet frame and armature core, are separate in the pole pieces air gaps, and armature teeth, in which almost all of the reluctance occurs hence for all practical purposes it is substantially correct to consider the machine as having two independently saturable flux paths, one along line $P1-P1$ and the other along line $P2-P2$.

To avoid a possible misunderstanding it should be noted that in Figure 3 the positions of the brushes as shown are diagrammatic only and represent the positions of the armature slot conductor at which they undergo commutation.

Commutation does not present any

greater problem than in an ordinary machine. Commutating poles are provided in accordance with usual practice. The commutation and characteristics are not sensitive to brush position, brush fit, or ordinary manufacturing variations.

Characteristics of the Exciter

In the circuit arrangement in which this exciter is used in the system, armature reaction and armature IR drop of the exciter tend, if not offset, to be of more than negligible effect, but they can be compensated sufficiently to make them almost negligible; consequently the explanation of the operation of the cross-flux exciter can be based upon a study of the no-load saturation curves of the respective flux paths. The upper part of Figure 4 represents the no-load saturation curve, not of the entire machine but of each of the two duplicate and practically independent flux paths, $P1$ and $P2$, respectively.

$H1$ represents the selected field strength of the separately excited main-field winding which remains substantially constant throughout. When the current in the cross field is zero, each flux path of the exciter causes the generation of a voltage E_a , and the total voltage generated is $2E_a$ plotted in the lower part of Figure 4 at zero cross-field ampere turns. Now assume a cross-field strength of $H2$. In flux path $P1$ the value of $H2$ is additive to $H1$, hence the voltage generated in this flux path is now E_a . In flux path $P2$ the value of $H2$ is subtractive from $H1$; hence the voltage generated in this flux path is now E_b . The total voltage generated is $E_a + E_b$, as plotted in the lower part of Figure 4. Since saturation increases beyond point E_a and decreases below E_a , voltage $E_a + E_b$ is substantially less than $2E_a$. At a cross-field strength of $2H2$ the further increment of voltage generated in path $P1$ is very small, but the decrement of voltage generated in path $P2$ is large—in fact the voltage of path $P2$ reverses. The corresponding total voltage $E_c + E_d$ accordingly is much reduced. When the two magnetic circuits are duplicate, and when the numbers of turns of the respective windings are equal upon all pole pieces, the negative voltage generated by path $P2$ cannot become quite so great as the voltage generated by path $P1$; hence the total voltage of the exciter never reaches zero. When the polarity of the cross-field current is opposite to the foregoing, path $P2$ behaves as did path $P1$ in the foregoing and conversely. Hence the

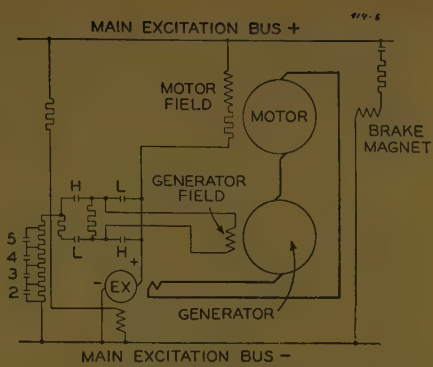


Figure 5. Elementary diagram—circuit arrangement of Ward-Leonard system using cross-flux exciter

characteristic of voltage generated versus cross-field (that is "loop" circuit) current tends to repeat symmetrically about the left-hand side of the vertical axis in the lower part of Figure 4. If compensation for armature reaction is not provided, this characteristic shows a departure from symmetry about the two sides of the vertical axis. The dissymmetry caused by armature reaction may or may not be practically disadvantageous, according to the specific design and application. To date, a design of exciter having closely symmetrical characteristics about the vertical axis has not been built. In the first design the armature reaction was not compensated. In a later design of a larger exciter the armature reaction was compensated, but a dissymmetry of characteristics was purposely introduced by means of unlike proportions of the respective flux paths.

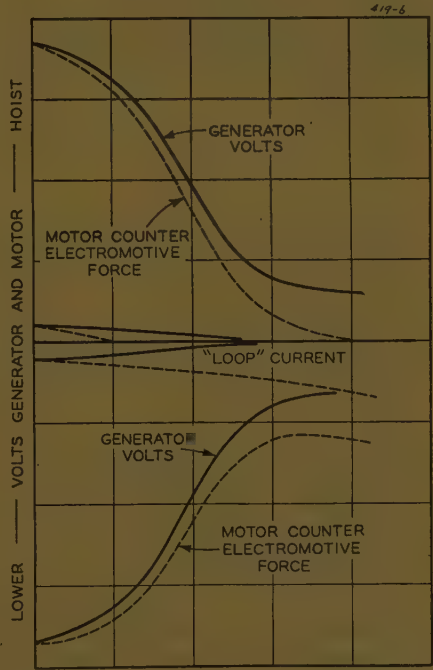


Figure 6. Theoretical characteristics—generator voltage and motor counter electromotive force of system of Figure 5

If a moderately greater value of separately excited field is held, represented by a higher value of H_1 in Figure 4, a voltage characteristic is obtained of similar shape having higher voltages throughout, and conversely for a moderately smaller value of separately excited field.

If the exciter of Figures 3 and 4 were only slightly saturated in each of its duplicate flux paths at the maximum cross-field current, its minimum output voltage (although substantially less than maximum) would not be so low as desired; hence a high degree of saturation is provided. This is done most suitably by providing a restricted section in each pole piece, for example by notches which are deep and also relatively long radially.

For reasons which will appear in the explanation of the system as a whole, it is usually important to offset or minimize the effect of IR drop of the exciter armature. Although not strictly necessary, it is usually advantageous to compensate the exciter for its armature reaction. By itself compounding may be provided by turns about each pole piece connected in series with the exciter armature, having polarities coinciding with that of main axis $m-m$. Perfect compensation for armature reaction tends to require a winding distributed over the pole arcs. Practically, however, a concentrated compensation provides all the benefit which is important. Such compensation can be provided by turns about each pole piece connected in series with the exciter armature, having polarities in line with the cross axis $C-C$. It might seem that for both of these improvements two field windings must be added to those of Figure 3. Actually only one added winding is required. Upon two pole pieces the polarities of the individual compounding and compensating windings would be alike, hence only one winding per pole piece is added having the sum of the turns individually required. Upon the other two pole pieces the polarities of the individual compounding and compensating windings would be opposed; hence only one winding per pole piece is added having the polarity and number of turns corresponding to the difference of the individual requirements.

Design and Arrangement of System

The generator is of normal design. Its main field is wound with the maximum practicable cross section of copper in order to provide the desired high no-load voltage with the least oversize of generator. Such a field winding provides a generator time constant which, in combination with

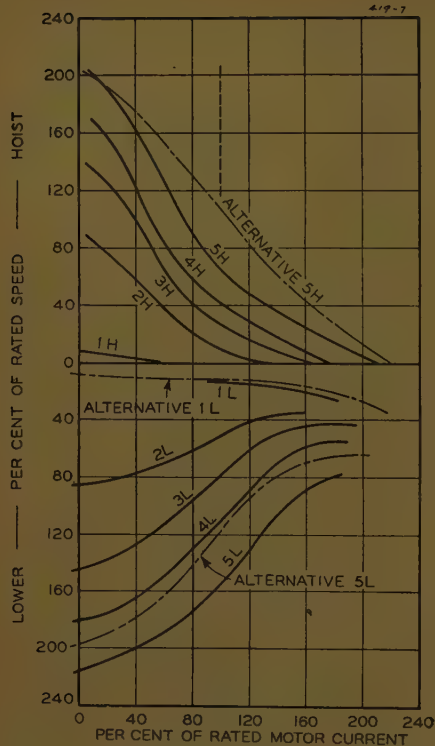


Figure 7. Characteristics from tests of developmental sample equipment

the circuit arrangement and cross-flux-exciter characteristics, limits the peak currents to values which are suitable for the electric equipment and the hoist system.

The generator, cross-flux exciter, and an ordinary constant-voltage exciter are driven by an induction motor, or if preferred for a sufficient reason by a synchronous motor or a d-c motor. An engine drive tends to be an improper choice, since the engine is unable to reconvert the energy regenerated by a descending load and hence is unable to restrain the speed of a descending load.

The hoist motor has a nonstandard main-field winding for a variable separate excitation but in other respects is of the type which is standard for high-class crane-hoist installations.

If it were intended to use the cross-flux exciter solely to furnish a generator excitation of the desired characteristics, it would be appropriate to consider an arrangement which connected the generator field directly to the armature of the cross-flux exciter, whereupon the hoist could be reversed and controlled by reversing and controlling the strength of the separately excited main field of this exciter. However, another important function of the cross-flux exciter is to provide an advantageous variation of the hoist-motor excitation. In order that one cross-flux exciter shall serve both of these purposes (by virtue of the unusual circuit arrangement used), it is necessary that the main-

field excitation of this exciter be maintained nonreversible and at a substantial value which is not far from constant. Accordingly, a conventional reversing control is provided between the exciter armature and the generator field, as indicated in the elementary diagram of Figure 5.

In order to provide the desired variation of the hoist-motor field, the cross-flux exciter is designed for a maximum voltage substantially less than that of the constant-voltage main-excitation bus. One terminal of the cross-flux exciter, negative as shown in Figure 5, is connected permanently to the main-excitation bus terminal of like (that is negative) polarity. Thus between the positive terminals of these two sources of excitation a variable voltage is available which is the difference of the two voltages. The hoist-motor field is connected permanently between these two terminals. The excitation voltage thus made available may be visualized by referring to Figure 4 and considering the ordinate between the lower and the upper base lines as the main-excitation bus voltage. Thereupon the height of ordinate from the curve "volts total" upward to the upper base line represents the voltage applied to the hoist-motor field. Thus the hoist-motor field is weakest when the "loop" current is substantially zero, which occurs when the empty hook is being hoisted and lowered and when the motor is at standstill at the "off" position of the controller. As the "loop" current increases, the decrease of the cross-flux-exciter voltage causes an increase in the motor-field strength. Normal field strength occurs at approximately rated armature current of the hoist motor. Typically the minimum field current is approximately 60 per cent of normal, and the maximum is approximately $1\frac{1}{2}$ normal.

This scheme of motor-field excitation provides three benefits:

1. Most important: an ample margin of torque stability is provided at all loads, both steady-state and transient.
2. A maximum speed of the empty hook is obtained which is moderately greater than that corresponding to the maximum no-load voltage of the generator.
3. Without any complication of contactors, relays, or the like in the motor-field circuit, the motor field continues strong at the "off" position of the controller during a retardation but is reduced to a value moderately less than normal while the hoist continues to stand at rest at the "off" position.

Because the cross-flux exciter is used for two purposes, its armature current is the difference of the generator-field and motor-field currents. Thus at zero "loop" current the exciter armature current is at its

maximum value as output. At rated "loop" current the generator-field current and motor-field current are nearly equal; hence the exciter armature current is not far from zero. At maximum "loop" current, when the exciter voltage is low accordingly, most of the hoist-motor field current becomes input into the exciter which accordingly acts regeneratively. The uncorrected effect of armature IR drop would be to decrease the maximum effective voltage of the exciter by a more than negligible percentage, but also to increase the minimum voltage of the exciter by a large percentage over the desired low value. It is principally for these reasons that the exciter is compounded as has been mentioned.

Certain optional features were added in the developmental sample, and tests were made both with and without their use. It was decided that the modifications of characteristics provided by these additions were not of sufficient importance to justify their inclusion in typical equipments. For this reason and because of space limitations these features are not described.

Speed-Torque Characteristics

The characteristics of the system are determined principally by the manner in which the generator voltage varies, subject, however, to the modifying effect of the IR drop of the "loop" circuit and the additional modifying effect of the motor-field variation. When the generator field is excited and controlled as described, the characteristics of generator voltage and of motor counter electro-

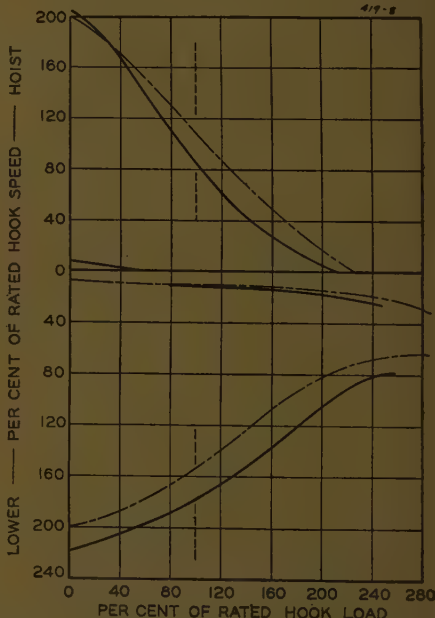


Figure 8. Calculated characteristics expressed as load on hook, from tests as in Figure 7

motive force with respect to "loop" current will resemble those of Figure 6, in which the curves of generator voltage represent not terminal voltage but voltage generated within the generator. In the upper right-hand quadrant, representing the hoisting of loads, the effect of "loop" circuit *IR* drop is subtractive from that of the generator voltage, but in the lower right-hand quadrant, representing the regenerative lowering of loads, this *IR* drop is additive. Hence the curves of motor counter electromotive force are not symmetrical in the hoisting and lowering direction, and upon any lowering position of the controller a stalled condition never occurs at any load, however large. If the hoist motor field were constant, the curves of motor counter electromotive force in Figure 6 would represent also the speed of the hoist motor. The effect of the variable motor field upon the speed-torque curves is to increase moderately the hoisting and lowering speeds at loads less than normal and to decrease slightly the speeds at overloads.

Figure 7 shows a set of speed-load characteristics from factory tests of the first equipment of this type. This equipment was a developmental sample for which only the cross-flux exciter, the control equipment, the brake magnet coil, and the hoist-motor-field winding were made for the purpose, the remainder

of the equipment being borrowed from stock. The loading arrangement provided a "live" counter torque, produced electrically and adjustable over a wide range, which provided an authentic simulation of the various loads upon a hoisting hook. In accordance with typical crane practice five speed-control positions were provided in each direction. The characteristics shown by curves 1*H* to 5*H* and 1*L* to 5*L* drawn in solid lines were obtained when using the optional features mentioned. The simpler arrangement, omitting the optional features, provided the characteristics shown in dot-dash lines, labeled "alternative." The corresponding "alternative" characteristic for slowest hoisting was almost identical with the curve 1*H* shown. From the test data the characteristics of speed versus load on

moderately higher speed when lowering rated load or overloads than when lowering the empty hook; hence they do not meet completely the sixth item in the list of ideal characteristics. However, these speed characteristics are superior in this respect to the characteristics 1*L* in Figures 1 and 2, which represent approximately the best of the standard practice heretofore. By improvements in design it is not difficult to make a further improvement over the characteristic 1*L* of Figure 7 without detracting from any other characteristics. This has been proved in the larger equipment of later design whose characteristics are shown in Figure 9.

With the possible exception of an extraordinary combination of conditions a crane is never called upon to lower a hook load greater than that which it is

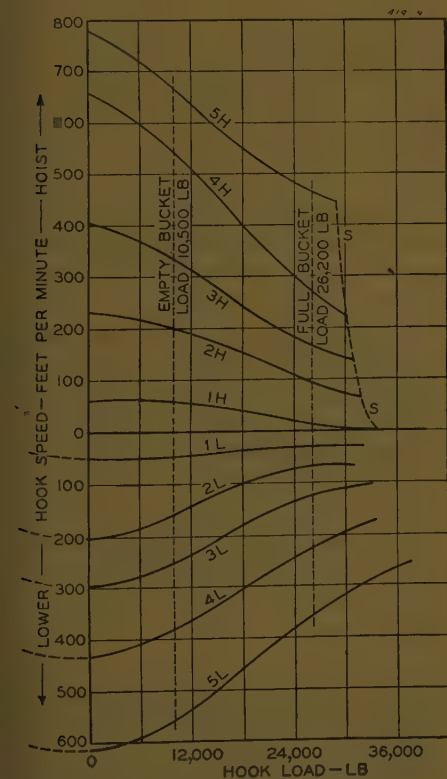


Figure 9. Characteristics of hoist of cantilever gantry crane, from tests of installation at Fontana Dam



the hook were calculated for the slowest and fastest speeds, as shown in Figure 8. These characteristics were calculated on the basis of an assumed mechanical efficiency of 87 per cent. In the author's opinion the "alternative" characteristics shown by the dot-dash lines are to be preferred.

The characteristics shown in Figure 7 and Figure 8 are considered to be particularly suitable for cranes in steel plants and heavy machine shops, subject to the possible exception that the highest-speed lowering characteristics there shown may be faster than considered desirable. It is a simple matter to readjust so as to reduce the speeds of the fastest lowering characteristic and to redistribute the intermediate characteristics accordingly.

The speed-torque characteristics upon the lowest-speed lowering position, curves 1*L* in Figure 7 and Figure 8 show a

Figure 10. Fontana Dam construction trestle equipped with two cantilever gantry cranes for handling four-cubic-yard concreting buckets, provided with variable-voltage hoist control using Whiting cross-flux exciter system and variable-voltage rack motion with floating-flywheel exciter

capable of picking up and hoisting. However, in the factory tests of the developmental sample electric "live" loads were applied equivalent to hook loads substantially greater than any which could be lifted, as shown in Figure 8. At such excessive loads curves 1*L* show increases in speed. These, however, do not involve any tendency toward instability but are merely the result of increased *IR* drop of the "loop" circuit throughout the excessive overloads at which the generator voltage is at a nearly constant minimum. Throughout the entire overload range the hoist-motor excitation

increases until at maximum overloads including those which are impossible in practice the motor is highly saturated, and hence in a very stable condition.

A large installation comprises two high-speed high-lift cranes used in the construction of a dam on the Little Tennessee River at Fontana, N. C. Although these cranes are very different from a typical steel-mill or heavy factory crane, the ideal characteristics enumerated in the introduction are especially desirable in this application. Because of the unusual character of these cranes certain additional requirements are imposed upon the speed-load characteristics of the hoist. Accordingly the electric equipment for the hoist was designed in accordance with the same principles but with certain changes in proportions and one additional feature.

These cranes are of a type sometimes called "hammerhead" but more aptly named cantilever gantry cranes. They have a maximum lift of 295 feet and at the extreme outward travel of the rack (that is trolley) motion the overhang of the hoisting hook at the end of either cantilever is 128 feet beyond the supporting tower. The hoist drive of each crane has a rms rating of 187 horsepower. These cranes are used at times for roustabout work, but their principal duty is the "pouring" of concrete.

During the earlier part of the construction schedule the crane picks up a bucket of freshly mixed concrete from a railroad car running between the legs of the crane tower, hoists the bucket sufficiently to clear the side rails, racks out the bucket to the required distance, and lowers it to the upper surface of the "block" being poured. When the bucket has been dumped, it is hoisted, racked in, and landed on the car. When the dam reaches nearly its maximum height, the loaded bucket will be lifted from the car a maximum of about 50 feet, and, after racking out, dumping and racking in, the empty bucket will be lowered to land on the car.

The purchase specification required that the speed of hoisting the loaded bucket be a relatively high percentage of the speed of hoisting the empty bucket but required also protection against an excessive overturning moment. Although the loaded bucket at its maximum overhang is entirely incapable of overturning the crane, it is possible when the crane is engaged in roustabout work that a hoisting hitch may be taken about an excessively heavy piece or an immovable object. Under the latter circumstances it is imperative that the hoisting effort shall be self-limiting to a value sub-

stantially less than the overturning moment of the crane.

In order to meet these requirements and at the same time retain the various other desirable characteristics, a cross-flux exciter was designed in which the two flux paths were purposely dissimilar whereby a set of speed-load curves was obtained as shown in Figure 9 based upon tests of the installation. In order to limit the stalled torque of the hoist motor to a value only moderately greater than its value for hoisting the maximum load in regular service, a simple addition was devised which causes the characteristics of the cross-flux exciter to break abruptly from the normal characteristic for which it is adjusted and at higher values of "loop" current to provide the stalling characteristic shown in Figure 9 by the broken lines S-S.

In addition to its adaptation to the special requirements just mentioned, the characteristics of this equipment provide two improvements over those of the developmental sample. The first-speed hoisting characteristic, curve 1H, is flatter. The first-speed lowering characteristic, curve 1L, goes all the way in meeting the seventh item in the list of ideal characteristics "... that the lowering speed be less at heavy loads than at partial loads or empty hook."

Transient Characteristics

As was predicted when the system was first devised on paper, the superior steady-state characteristics and the means by which these characteristics are obtained contribute to the creation of favorable transient operating characteristics during the course of ordinary accelerations, retardations, and reversals, and during emergency stops. Because the maximum speed when lowering a heavy load is much less than when lowering a light load or the empty hook, the kinetic stored energy of the hoisting system is inherently reduced whenever increased hook loads are being lowered. Under these conditions the generator-field current is also much less than maximum; hence at a quick movement of the controller from full speed to the "off" position (or to a hoisting position) the initial rate of decay of generator field is much less than maximum. At the heavier loads the motor field is strong, and an increase of "loop" current for the retardation causes a further increase of motor-field current. From the combination of these phenomena it comes about that the retardation of heavy descending load requires a "loop" current only moder-

ately greater than that of the speed from which the retardation is begun and only a little greater than that for retarding the empty hook from its maximum speed.

This combination of phenomena is similarly and equally beneficial with respect to the retardation and stop under emergency conditions such as failure of incoming power. It has been observed that when maximum load is being lowered at its maximum speed an emergency stop requires only slightly more current from the hoist motor than is required for the corresponding emergency stop of the empty hook and little more than for a normal retardation at the maximum rate.

Conclusion

The hoisting-machinery art includes many different types of equipment for widely different applications. Some of these types of hoist have relatively unexacting requirements which are met acceptably by various simple systems of electric drive. Several systems of electric-hoist drives have been developed, each of which has certain specialized modifications which are particularly advantageous for certain exacting applications but which are irrelevant or disadvantageous for certain other hoisting applications whose requirements are equally exacting but different. The electric system described in this paper is not to be considered as preferable or even applicable for every important type of hoist, but it is intended for use in several types of hoist in which, notwithstanding certain substantial differences of design and use, the speed-torque requirements are similar.

No installations have yet been made in large heavy-duty indoor cranes such as are typical of steel plants and heavy machine shops. However, the results first demonstrated by the developmental sample and confirmed in practice by the Fontana Dam installation indicate the suitability and advantages of the system for heavy-duty indoor cranes. It seems reasonable to expect that with further experience and additional study of details and refinements the field of application will be broadened further.

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Gear Ratio and Its Effect on Traction Motors

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Synopsis: The mechanical power delivered by the motors of electrically propelled vehicles is almost always transmitted through gears to axles. The few exceptions are some gearless electric locomotives designed many years ago. Although the top speeds of vehicles and locomotives have increased materially since the inception of electric drive, the very nature of the service requires high tractive efforts in starting from standstill and at low speeds. In the case of transit vehicles, frequent stops require operation at relatively low speeds a large percentage of the time.

The history of traction-motor design discloses a trend toward higher and higher motor speeds. These higher speeds have resulted in reduced motor weight and space requirements, which are two most important considerations in traction apparatus. In order to use motors of higher speed economically, greater gear reductions are required. As developments in gear design, gear materials, and heat treatments progressed, greater gear reductions became practicable, and the higher-speed motors came into general use. Modern double-reduction gear units and hypoid gears permit greater gear reductions and, hence, higher motor speeds than the single-reduction spur gears which were once employed in all traction applications.

The reductions in weight and size of traction motors are not only advantageous in themselves, but they permit features in vehicle construction which add to the comfort and convenience of passengers and to over-all economy of operation. This paper discusses some of the elementary considerations of gear design and includes a specific example of the effect of change in gear ratio on traction motors.

THE electric motor is extremely well adapted to high-speed operation. The higher the speed at which it can be operated, within limits, the lighter and more compact the motor. The wheel speeds of electrically propelled vehicles and locomotives are quite low by comparison, because they have to start from zero speed at frequent intervals, and even at top vehicle speeds the wheel speed is still too low for economical gearless motor

design. As a result, practically all propulsion motors are geared to the axles, the gear reduction serving the usual two-fold purpose of reducing the speed and multiplying the torque. As improvements in gear materials, heat treatments, and designs have made greater reductions practicable, it has been possible to utilize economically motors of higher speed. Streetcar motors serve as a good example of this trend, because they were the earliest traction motors, and continued progress has been required to keep streetcars competitive with other forms of transportation.

Early Motor Designs

All early traction motors were supported at one side by bearings on the axle and on the other by a connection to the car or locomotive truck. The distance between the center of the pinion, mounted on the motor shaft and the center of the gear, mounted on the axle was fixed for each motor frame. This gear-center distance is SA in Figure 1A. This distance is divided into two parts, SB and BA , so selected that BA divided by SB gives the speed reduction desired. The two circles shown with A and S as centers are known as pitch circles of the gear and pinion, respectively. The gear teeth are laid out around these circles.

Let us assume that the gear-center distance of a particular motor was 14 inches and the diametral pitch of the gears three. The total number of teeth in gear and pinion was $3 \times 2 \times 14 = 84$. The values selected are typical of the gears used on 40- and 50-horsepower 500-volt streetcar motors 35 to 40 years ago. At that time a 15-tooth three-diametral-pitch pinion was the smallest in general use, because a smaller pinion did not have sufficient strength between the root of the tooth and the bore, or at the keyway, with the best material available at that time.

In the example selected there must be $84 - 15 = 69$ teeth in the gear. The diameter over the ends of the gear teeth was $(69 + 2)/3 = 23.67$ inches. With new wheels a clearance of four inches between top of rail and bottom of gear case was considered essential to avoid hitting the

gear case on obstructions in the street. The outside diameter of the gear case was approximately one inch greater than the diameter over the ends of the gear teeth to allow for clearance in the gear case and thickness of the gear case. Therefore, the diameter of the new wheel could not be less than $23.67 + 1 + 8 = 32.67$ inches, and 33-inch wheels were in common use. They were worn to a minimum diameter of 30 inches; thus, the clearance under the gear case was reduced by 1.5 inches. The limitations of pinion and gear design made gear reductions of 4.6:1 general and 33-inch wheels a standard for city cars.

The streetcars of this period weighed 50,000 pounds and were propelled by four 40- or 50-horsepower 500-volt motors, depending to a great extent on the grade conditions of the city in which they were operated. The clearance between the top and the rail and the bottom of the motor frame, with 33-inch wheels, was also approximately four inches. The 40-horsepower motor weighed 2,800 pounds, complete with gear and gear case, and 2,400 pounds without gear and gear case. The maximum safe speed of the motor was 1,900 rpm, which resulted in peripheral speeds of 7,000 feet per minute of the armature and 5,100 feet per minute of the commutator.

There was not much change in motor speeds for a number of years, although progress was made along other lines. Motors with commutating poles became standard, and ratings were based on 600 volts with a resulting increase in horsepower of 20 per cent. Bearings and shafts were improved. Better gear materials were used, and heat treating became general. Progress was made in insulating materials. During this period the traction motor progressed from the state where normal life of pinions, bearings, windings, brushes, and commutators was short to where life of these parts was increased several times.

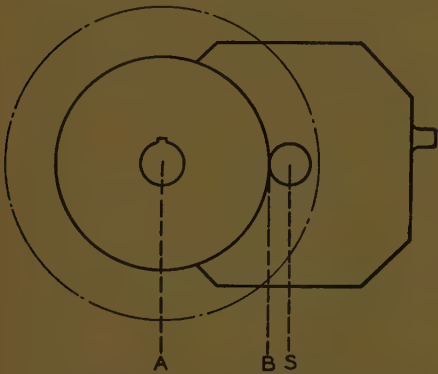
New Motor Designs and Low-Floor Cars

The year 1912 marked a traction-motor and streetcar development which radically changed the appearance of streetcars and the ease with which passengers could board and alight from them. The Pittsburgh Railways Company designed a car with 24-inch wheels and correspondingly low-car floors. The car seated 55 passengers, and its weight was only 34,000 pounds. Four 35-horsepower 600-volt motors were adequate for even the severe grade and traffic conditions of Pittsburgh.

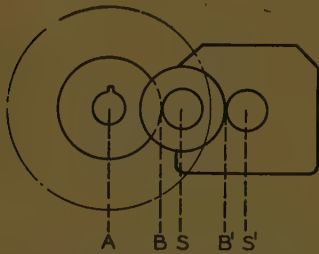
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The design of a motor for 24-inch wheels was an undertaking of considerable magnitude at that time. The motor developed was known as the Westinghouse type 328. It was self-ventilated by means of a fan on the armature shaft, and in the original design the coils were "bakelized." Gears of 3.5 diametral pitch were used, and the face of the gears was four inches instead of five inches, as used previously. The use of the $3\frac{1}{2}$ -pitch gears made it possible to get the required reduction in the space available. Because of progress in gear construction, these gears proved entirely satisfactory. The clearance under the motor frame was $3\frac{1}{4}$ inches



A. Motor with single-reduction gears



B. Motor with double-reduction gears

Figure 1

and under the gear case three inches. This sacrifice of one-inch clearance meant that, for parallel street conditions, the wheels could not be worn to the same extent as on the older cars. Actually, the 24-inch wheels were later superseded as standard by 26-inch wheels, thus increasing clearances one inch.

The gear-center distance of the new motor was 10.43 inches, making a total of 73 teeth. A 15-tooth 3.5-pitch pinion was the minimum permissible. The maximum reduction-gear ratio was 58:15 or 3.87:1, but this gear reduction with 24-inch wheels is equivalent to a reduction of 5:32:1 with 33-inch wheels.

The maximum safe armature speed of the motor was 2,600 rpm. At this speed the peripheral speed of the armature was 6,800 feet per minute and of the commutator 5,800 feet per minute. While the maximum safe speed of the armature was

raised 37 per cent, the peripheral speed of the armature was held essentially the same by reducing the diameter, and the peripheral speed of the commutator was increased only 14 per cent. The motor complete with gear and gear case weighed 1,680 pounds or a reduction of 40 per cent compared with the 50-horsepower 500-volt (60-horsepower 600 volts) motor used on the heavier cars. The total weight saving, due to the four lighter motors, was 4,480 pounds. The saving, due to using 24-inch instead of 33-inch wheels and the resulting lighter truck structure, was 4,000 pounds. Other weight economy was effected in the car body.

For the next 15 years street-railway motor design followed the trail blazed by this first motor suitable for low-floor cars. In a few years ventilated motors suitable for 26-inch wheels were available in 25-, 40-, and 50-horsepower sizes. A gear reduction of 5.7:1 was used on 25-horsepower motors, gears of $4\frac{1}{4}$ diametral pitch being employed. Again, there was a period of perfecting of details and consolidation of advances.

One of the latest axle-hung motors

Separate Gear Units

In 1927 a radical change in method of transmitting motor torque to the street-car axles was tried experimentally. Worm gears were used. The time-honored axle-hung motor, sleeve bearings, grease-lubricated spur gears and split gear case was a crude noisy arrangement by private automobile standards. It did function successfully. Two cars were constructed using worm-drive axles, including differential gears, which were an outgrowth of bus and truck axles. Oil-lubricated gears in a dirt-tight case were employed. The gears were silent. Gear ratios of 10:1 were available. The separation of the gear unit from the motor removed the restriction of gear center distance as a determining factor in gear ratio and allowed the most economical motor speed to be selected.

On the first experimental cars high-speed motors, developed primarily for gas-electric bus service, were applied. These motors were soon superseded by a high-speed railway motor specifically developed for the service. This motor rated 35 horsepower and had a maximum safe

Table I. Comparison of Traction Motors

Horse-power	Volts	Gear Ratio	Wheel Diameter—Inches	Total** Reduction	Maximum Safe Speed—Rpm	Peripheral Speed Feet Per Minute		Bare Motor Weight—Pounds	Miles Per Hour at Maximum Rpm	Clearance (Inches)
						Armature	Commutator			
40...	500	4.6:1	33	0.0213	1,900	7,000	5,100	60.0	40	4 1/8
50...	600	4.6:1	33	0.0213	1,900	7,000	5,100	47.8	40	4 1/8
35...	600	3.87:1	24	0.0185	2,600	6,800	5,800	42.6	48	3 1/4
50...	600	3.78:1	26	0.0204	3,000	8,650	7,060	38.8	61	3 3/4
35...	300/600	9:1	22*	0.0073	5,000	11,100	9,500	16.3	36.5	5
55...	300/600	7.17:1	25	0.0104	5,000	12,100	9,300	12.7	52	6

* With WN double-reduction drive.

** Rpm X total reduction = miles per hour Total reduction = $\frac{\text{wheel diameter}}{336 \times \text{gear ratio}}$

developed had a one-hour rating of 50 horsepower at 1,000 rpm. It weighed 1,940 pounds without gear and gear case and 2,185 pounds with gear and gear case. It had a gear reduction of 53:14 or 3.78:1 when gears of three diametral pitch were used. The maximum safe speed of armature was 3,000 rpm. The corresponding peripheral speed of the armature was 8,650 feet per minute and of the commutator 7,060. The car speed corresponding to 3,000 armature rpm was 61 miles per hour. While the peripheral speeds were raised at the maximum safe armature speed, the corresponding car speed was so high that it was rarely, if ever, reached in urban service.

armature speed of 5,000 rpm. The maximum armature peripheral speed was 11,100 feet per minute, and the maximum commutator peripheral speed was 9,500 feet per minute. The motor weight was 570 pounds. Since the motors were entirely spring suspended, lighter-weight construction was more practicable than it was in former designs, where they were subjected directly to all the impacts of the wheels on rail irregularities. The worm-drive axles proved to be unsatisfactory in railway service, but they hastened the development of much-higher-speed motors than were previously used and other forms of gear drive which have proved satisfactory.

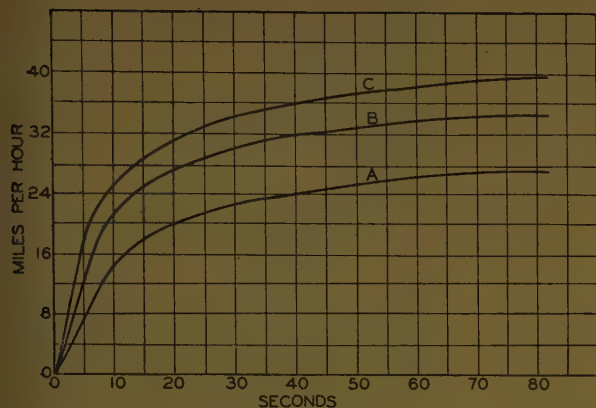


Figure 2. Speed-time curves

The application of worm drive to streetcars was followed very quickly by the development of a double-reduction and a single-reduction self-contained gear unit which possessed most of the advantages of the worm drive. When the gear teeth were ground, the accuracy of tooth contact was improved. Antifriction bearings maintained gear-center distances accurately. As a result, the gear noise was reduced so greatly that the average passenger was not conscious of it. Also, gears of higher diametral pitch were used successfully. The double-reduction unit employed high-speed gears of $4\frac{1}{2}$ diametral pitch and the low-speed gears four. Phenomenally, long gear and bearing life was obtained. The spur gear units were more efficient than the worm drive.

The double-reduction drive permitted the use of wheels having a diameter of 22 inches with 4.5 inches clearance under the gear case. Figure 1B illustrates the double-reduction gear arrangement. The maximum gear reduction was 9:1, although most applications were made with less reduction in order to obtain the higher car speeds which were coming into general use. The single-reduction drive provided a maximum reduction of 7:1 and required 26-inch wheels to give $3\frac{3}{4}$ inches clearance between top of rail and bottom of gear unit.

Presidents' Conference Committee Car

Just at the time that these drives were proving their worth in service, the Electric Railways Presidents' Conference Committee was engaged in designing a com-

Table II

Car	Schedule Speed (Miles Per Hour)	Kilowatt-Hours Per Car Mile
A	10.4	3.6
B	12.5	4.4
C	14.4	5.3

Car A. 48,000 pounds empty, 6,000 pounds passenger load, four 40-horsepower 500-volt motors, 69:15 gear ratio, 33 inches wheel diameter

Car B. 38,800 pounds empty, 6,000 pounds passenger load, four 50-horsepower 600-volt motors, 53:14 gear ratio, 26 inches wheel diameter

Car C. 33,000 pounds empty, 6,000 pounds passenger load, four 55-horsepower 600-volt motors, 7.17:1 gear ratio, 25 inches wheel diameter

pletely new streetcar. New standards of performance in rates and smoothness of acceleration and braking, speed, passenger comfort, heating, ventilation, and lighting were established. Entirely new car body and car trucks, including rubber-cushioned wheels, were developed. A right-angle drive (motor shaft at right angles to axle) was selected, because it was better fitted to the truck design, was believed to be inherently quieter than the double-reduction spur gears, and was less expensive. The drive selected consisted of hypoid gears with 7.17:1 reduction. Antifriction bearings and oil lubrication were used. This drive embodied the advances of automotive-gearing design and has operated most successfully.

The new standards of performance required the design of a new motor having a one-hour rating of 55 horsepower. The four motors not only propel the car but do most of the braking dynamically. The dynamic braking is supplemented by electrically operated track brakes and air-operated brakes on the car wheels or

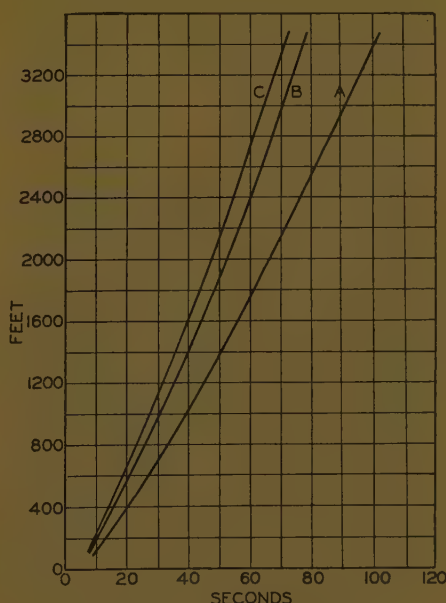


Figure 3. Distance-time curves
Cars A, B, and C as in Figure 2

Table III

Gear Ratio	Schedule Speed (Miles Per Hour)	Kilowatt-Hours Per Coach Mile	Root Mean Square Amperes
9.2:1	15.7	2.7	156
11.4:1	15.2	2.4	131

electrically operated drum brakes on the armature shaft. The energy dissipated in the accelerating and braking resistors is used for heating the car during cold weather.

The new motor weighs 700 pounds and has a maximum safe speed of 5,000 rpm. At 5,000 rpm the peripheral speed of the armature is 12,100 feet per minute and of the commutator 9,300. The corresponding maximum car speed is 52 miles per hour. Wheels of 25-inch diameter are used. The clearance under the gear housing is $4\frac{1}{4}$ inches. The motors are completely spring-born, and, therefore, their height above the rail varies somewhat with passenger load. Normally, it is six inches.

For convenience of comparison Table I shows the principal characteristics of the various motors which have been discussed. They are typical of the streetcar motors used at various times in the past 40 years. Worthy of note are the increase in total reduction, the consistent increase in maximum safe speed, and in armature and commutator peripheral speeds. Although these changes did not accompany improvements in gearing step by step, they were in large measure the

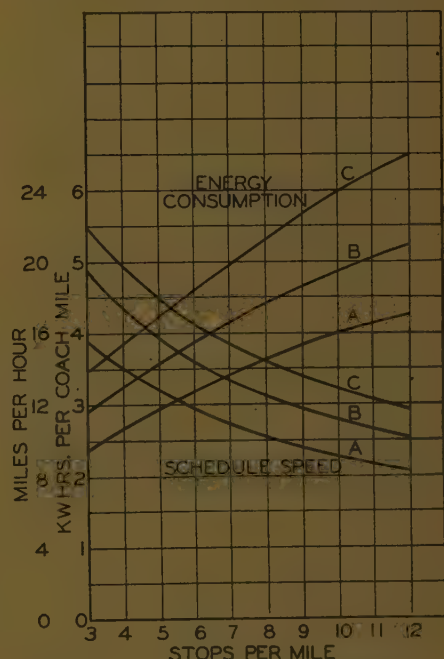


Figure 4. Operating-characteristic curves
Cars A, B, and C as in Figure 2

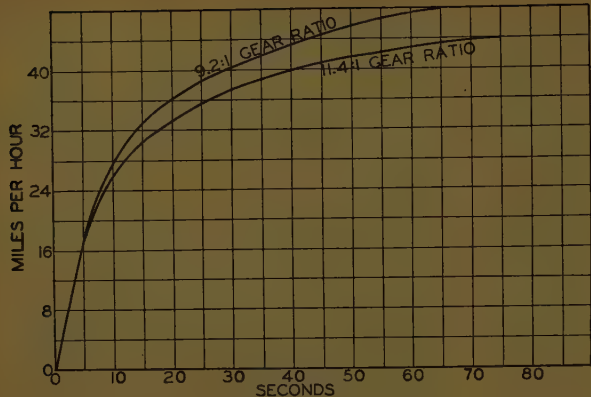


Figure 5. Speed-time curves
Trolley coach with 9.2:1 and
11.4:1 gear ratios

result of gradual gear evolution. Cast iron and malleable iron were superseded by cast steel, forged steel, and alloy steels. The $14\frac{1}{2}$ -degree involute tooth form was superseded by 20 degrees involute, thus increasing strength. Long and short addendum pinions and gears were adopted with resulting greater pinion strength and more metal between root of tooth and pinion bore. Therefore, smaller pinions can be used. Water quenching, oil quenching, case hardening, and flame hardening were introduced.

Figure 2 shows the comparative speed attained in a given time by three types of cars. Car *A* is one typical of those in use 40 years ago. Car *B* represents the best type of car with axle-hung motors, available in the late 1920's. Car *C* is the modern PCC car. To attain a speed of 25 miles per hour requires 48 seconds for car *A*, 16 seconds for car *B*, and 10 seconds for car *C*.

Figure 3 shows the distance covered by each car for various moving times. A distance of 1,000 feet is traversed in 39 seconds by car *A*, 31 seconds by car *B*, and 27.5 seconds by car *C*.

Figure 4 shows the schedule speed in miles per hour and the energy consumption in kilowatt-hours per car-mile for various stops per mile between 3 and 12. The comparison at eight stops per mile is shown in Table II.

It should be understood that these values are theoretical, and, that, in actual practice both schedule speeds and energy consumption are lower for all three cars than calculated. Although the energy consumption of car *C* is relatively high, it affords a superior service which requires more power. High-schedule speeds not only appeal to the patrons, but the wages of car operators per

car-mile vary inversely, as schedule speed and operators' wages are the principal item of operating expense.

Trolley-Coach Performance

The trolley coach is selected as the means of illustrating the effect of gear ratio on traction-motor performance for a given set of conditions. Modern streetcars are standardized to such extent that the same gear ratio is used in all applications. Various gear ratios are applied on trolley coaches. Figure 5 shows the comparative speeds of a typical trolley coach with gear ratios of 9.2:1 and 11.4:1. Trolley-coach gear ratios are greater than streetcar ratios, because the rubber-tired wheels have an effective diameter of 40 to 43 inches instead of 25.

Figure 6 shows the schedule speed and energy consumption for a typical trolley coach with each gear ratio. Not only are schedule speed and energy consumption increased by decreased gear reduction, but also motor rms current is increased. At six stops per mile the comparison is as indicated in Table III. The percentage increase in schedule speed is small compared with the increase in energy consumption and rms current.

Conclusion

It is apparent that great progress has been made in the performance of vehicles on the street as the direct result of progress in motor and gear design. There has been equally great progress made in car design as a result of less space and weight required for motors. When wheel diameters are reduced from 33 inches to 25 inches, car floor height is reduced a corresponding amount. This results in

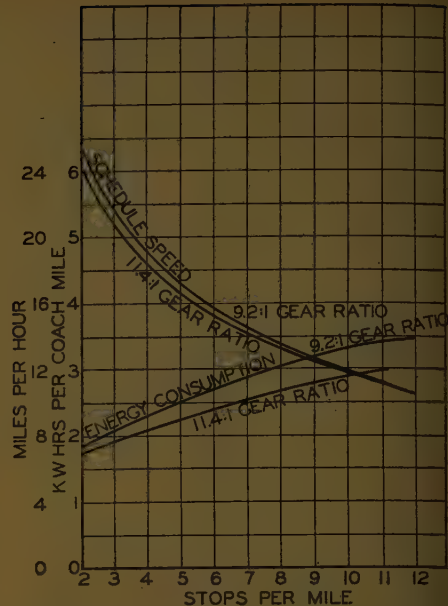


Figure 6. Operating-characteristic curves
Trolley coach with 9.2:1 and 11.4:1 gear
ratios

one less step, which, in turn, means greater safety, less boarding and alighting time, shorter stops, and, hence, higher schedule speeds.

All are familiar with the outward changes in streetcars and trolley coaches. Unfortunately, too many examples of old street cars are in evidence for one to forget their outstanding characteristics. The more pleasing appearance, smoother and quieter operation, and better ventilation and heating in new streetcars are indirect results of progress in motor design.

Higher motor speeds brought with them improved commutator and armature construction and dynamic balancing. Better insulating materials, notably the general use of class-B instead of class-A insulation, and more effective ventilation, have made important contributions to reduced size and weight. Greater gear reduction has been essential to the economic application of these higher-speed motors.

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The Effect of Kilovar Supply on the Design of Systems for Load Growth

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THE benefits that can be obtained by the use of shunt capacitors in electric power systems have been discussed many times in the technical literature. Their ability to improve voltage and power factor in the distribution areas, thereby reducing losses and postponing the need for additional circuit capacity by reducing loading on existing equipment, has been used many times where the economics have justified such use.

Again, other discussions have shown that the greatest use of a given total system investment may be obtained when the basic kilovar requirements are supplied near the load by either capacitors or condensers. It is the purpose of the present paper to combine these two major thoughts by investigating the place of the capacitor in providing for load growth on a specific system. This approach will give some indication of the economics and the benefits to be gained on an over-all system basis, which in the final analysis is the most logical view to take.

In many cases kilovar supply by capacitors, for a single purpose, such as voltage improvement, reduction in transformer, line or cable loading, may not be justified, as other means may permit a lower first cost (as will be shown), but when these effects are viewed jointly and evaluated on a system-wide basis, a different conclusion may result.

Basis of Analysis

To permit a study of the possibilities of capacitors as a stepping stone in system growth, a type of power system using modern design principles was assumed. Although a synthetic system, electrical details of the circuits were worked out from the residential customer entrance

and commercial and industrial customer transformer secondary circuits back to the generating plant. This was called the present system. Then each portion of the system was redesigned to enable it to carry a load increase which would be obtained at some future time, the new load and system being designated as future. The kilowatt portion of the load increase viewed at the generating plants amounted to 67 per cent, although this percentage varied somewhat for each individual portion of the system. The necessary design changes made in the present system to derive the future system capable of carrying the increased loads, were made to each of the various parts in two ways:

1. By replacing present conductors, transformers, and regulators with larger ones, or adding to such equipment.
2. By supplying part of the future load kilovars by capacitors, thus reducing the extent to which other equipment had to be increased.

Estimated installed cost figures were applied to the two methods for economic comparison, and the future system was set up both ways on the network analyzer to permit a comparison of over-all operating performance.

In general, the various feeder circuits were designed in either case with the same amount of margin for a still further increase in load, or so-called slack.

Conclusions

It will be realized that the area, within the system in which the use of capacitors shows an economic gain, depends very greatly on the character of the system in question. Where the unit or small substation principle is applied making the low-voltage heavily loaded circuit runs comparatively short, the gains are less in the distribution areas by themselves. This principle of system design tends to shift the major benefits from the distribution to other parts of the system.

The type of system selected in this study employed the unit- or small-substation principle quite extensively, as will be discussed more in detail later; so this fact should be borne in mind in considering the following conclusions.

These conclusions must, of necessity, apply rigorously only to the system studied, although certain generalizations will be apparent from them.

1. Exclusive of the increased generating-plant facilities to care for the future requirements (which were the same in either case), the use of capacitors resulted in an over-all saving of approximately \$262,400 on a \$2,500,000 investment, or about 10 per cent.
2. The total estimated cost of changing only the feeder circuits to accommodate the increased loads, either with or without capacitors, was about the same. In one type of feeder the cost of using capacitors would be greater than that of increasing the materials or adding feeder voltage regulators, and so forth, whereas in another the relative cost would favor the capacitor, and, in the aggregate, on the system studied the cost was about a standoff.
3. The greatest differential in cost of increasing the capacity of the feeder circuits favoring the capacitor method occurred in the residential-type feeders, where the improvement of the first-to-last customer voltage of the single-phase lateral circuits with capacitors precludes the need of adding conductors and reconnecting for three-phase, which must be done for voltage purposes, if capacitors are not used.
4. The greatest differential in cost favoring not using capacitors was on the 33-kv feeders supplying industrial power at 33 kv where strictly no change to the feeder was required to enable it to carry the future load. A large capacitor bank was added, however, at the end of each of these for the capacitor case, because this would be a logical location in this system for a kilovar source in such a program.
5. The total estimated cost of changing the substation and subtransmission facilities, if capacitors were used on the feeders, was \$139,500 as compared with \$383,700 if capacitors were not used.
6. The operating margin in the generating plants under future load with capacitors was increased by a reduction in system losses of 7,900 kw and 34,000 kilovars on a system-delivered peak load of 255,000 kw. The additional margins provided would allow the system to operate with one less hydrogenerating unit under emergency conditions, if steam and prime-mover capacity were available. This is seen clearly in Figure 11.
7. It is well known that in systems using long heavily loaded feeders, capacitors offer the largest gains. This study indicates that in systems where such feeders are eliminated mainly by employing the unit- or small-substation principle of design, the use of kilovar source near the load still is justified on an over-all economic basis, from the standpoint of both first cost and operating efficiency. Thus, systems using modern design extensively may use to an advantage a co-ordinated system program of kilovar planning.
8. System incremental load losses are twice the actual per-unit load losses in the regions of practical system operation. This

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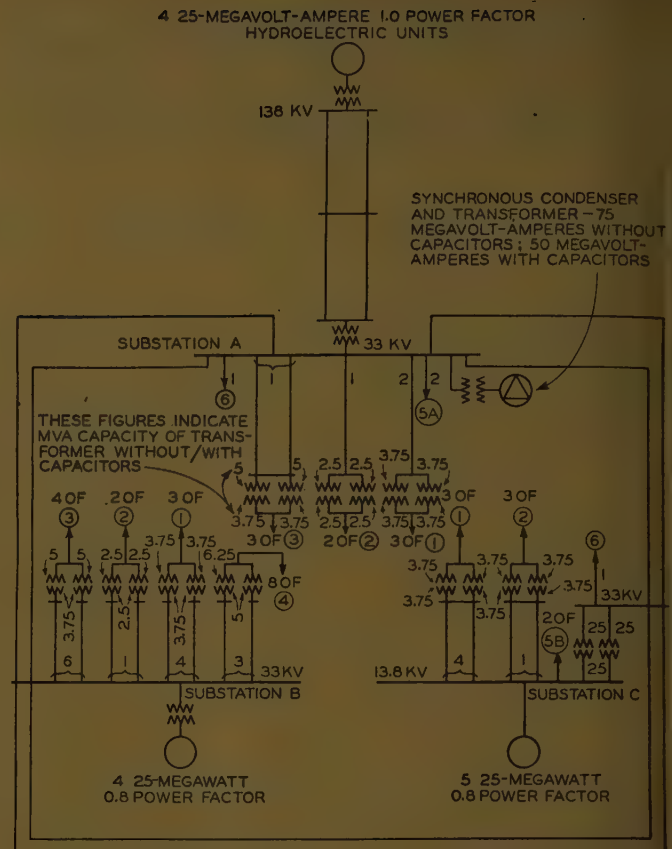
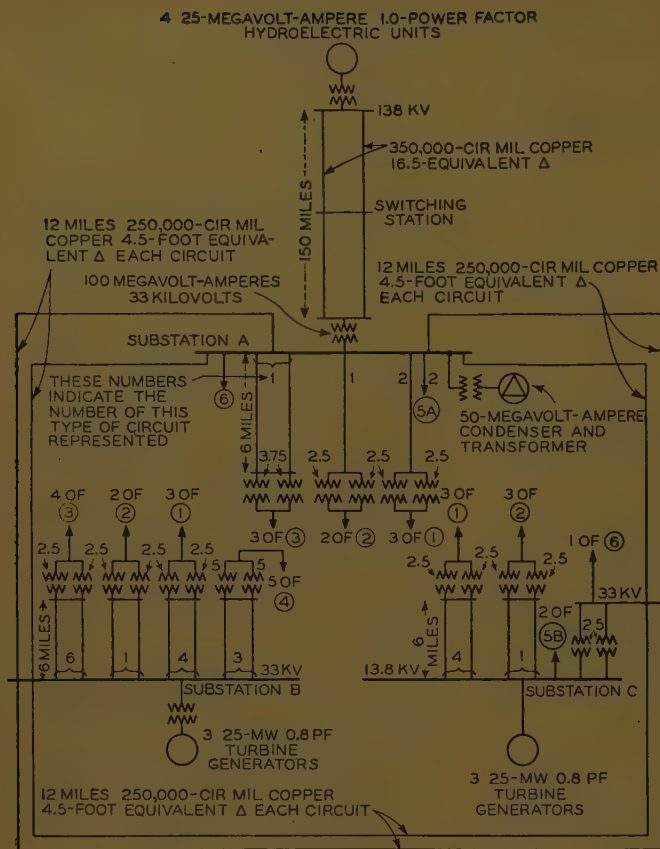


Figure 1. System layout. Present loads

All 33 kv is overhead. Six-mile circuits from generator to feeder substations are overhead; 4/0 copper 3.5 feet equivalent Δ spacing

Feeder Loads—Present

Circled Number	Type	Kilowatts	Kilovars
1.... Residential.....		1,000....	483
2.... Commercial.....		1,000....	750
3.... Industrial.....		1,000....	882
4.... Commercial network.....		15-1,000....	750
5A.... 13.8-kv industrial, 33-kv line.....		13,000....	11,500
5B.... 13.8-kv industrial, 13.8-kv line.....		13,000....	11,500
6.... 33-kv industrial, 33-kv line.....		14,000....	12,400

applies for circuits that maintain voltage by kilovar supply at either end, as well as for circuits using a regulator at the sending end to maintain receiver voltage.

Statement of the Problem

DESCRIPTION OF SYSTEM

1. *General.* The system was set up and studied, as shown in detail in Figures 1 and 2. It is composed of three major load areas, each with a present load of about 50,000 kw and each connected to the other by a double-circuit 33-kv belt line 12 miles in length. Two of the load areas are supplied by a local steam-generating plant each, and the third by a hydroelectric plant 150 miles distant supplying its kilowatt requirements over a two-circuit 138-kv line,

with an intermediate switching station, needed for transient stability. Kilovar requirements of this load area are supplied by a synchronous condenser feeding the 33-kv substation bus. Each generating plant is capable of carrying the load requirements of its own area; hence, power flow over the belt lines is restricted to emergency conditions. Most systems would generally operate part of its sub-transmission facilities loaded during normal peak-load conditions, the effect of which would be to favor the capacitor case; so the results are considered very conservative.

2. *Feeders.* Types, loads, and distribution among substations: Feeder types and loads are classified in the tabulations accompanying Figures 1 and 2 for present and future loads, respectively. The design and performance details of each type of feeder, for present load, future load without capacitors, and future load with capacitors, are given in Figures 3 to 9, inclusive.

Table I indicates the distribution of types of loads and feeders among the three substations.

For purposes of this study it was deemed satisfactory in the interests of simplicity to use the same feeder of each type at all three substations. This, of course, is not a condition that would occur in practice, but if the feeder length and load are considered an average value,

Figure 2. System layout. Future loads with and without capacitors. Other details same as Figure 1

Feeder Loads—Future

Circled Number	Type	Kilowatts	Kilovars	Kilovars With Capacitors
1.... Residential...		1,800...	876...	335
2.... Commercial...		1,800...	1,350...	870
3.... Industrial...		1,500...	1,350...	490
4.... Commercial network.....		24-1,100...	825...	533
5A.... 13.8-kv industrial, 33-kv line.....		19,500...	17,250...	9,460
5B.... 13.8-kv industrial, 13.8-kv line.....		19,500...	17,250...	9,460
6.... 33-kv industrial, 33-kv line.....		21,000...	18,600...	10,140

the results produced should reasonably approach those that would obtain on an actual system.

ALTERNATIVE METHODS OF HANDLING LOAD GROWTH

Figures 3 through 9 indicate the alternative methods of providing for future load growth in the various feeders, and the detailed changes required for each method are listed in Table II. For the no-capacitor case the addition or enlargement of circuits and transformers and/or voltage regulators was resorted to in order to overcome the voltage drop or thermal-capacity limitations. For the

capacitor case these limitations were overcome entirely or in part with capacitors, depending upon the details of each individual case.

These feeders were then represented as loads on the system, as shown in Figure 2, set up on the network analyzer. The normal and emergency performance of the system could then be studied with and without capacitors, and the effect of these capacitors on the system evaluated in terms of subtransmission system and distribution substation capacity needed. Table III and Figure 2 summarize the detailed changes needed to the system to enable it to carry the future loads of the feeders designed with and without capacitors.

PRESENT AND FUTURE LOADS

Details of individual feeder designs are given in the figures; hence, they need not be discussed here. It may be noted that the margin for growth beyond present loads is not necessarily the same in each of the feeders, nor is the percentage of growth to future loads exactly the same among the feeders. This fact does not affect the qualitative result of the economic comparison between the use of capacitors and the use of other means to provide for the load growth, but it obviously might affect the degree of the economic unbalance of the two methods. The values of present and future loads were taken at random; since, on an actual system they could, of course, be any value over a given period of time and would probably not be the same on each of the different types of feeders.

It is fair to expect, however, that feeder and system capacity be reasonably equally used up, that is, the margin for growth beyond future loads be the same, regardless of the method used to provide for the load increases. This is, in general, true, as will be shown by the following brief comparative comments on the margin remaining in each type of feeder, for the two methods. The numbers identifying the feeder types in Figure 3 through 9 correspond to the following numbered sections:

1. *Residential Feeder.* Changing single-phase laterals to three phase to cut down unregulated voltage drop in these sections reduces the voltage drop more than the simple addition of enough capacitors at the end of existing single-phase laterals to make the voltage drop acceptable, as was done in the capacitor case. This is not the discrepancy it first appears to be, however, because the future load is about the ultimate for the load area (as indicated by the load density)

served by the feeder, and, even if this were not the case, the cost of achieving the same voltage drop with capacitors, as compared with changing over to three-phase laterals, would still be less.

2. *Commercial Feeder.* Cable ampere capacity is the limitation to increased load. If a parallel cable equal in size to the original were run, the capacity would be increased from 275 amperes to 550 amperes, whereas the capacitors added simply brought the future uncorrected load current of 312 amperes back to 275 amperes. Thus, by adding the cable, pro-

itor case to hold the voltage drop to the adopted values. No margin is thus left for additional load without adding equipment for either case.

4. *Commercial Network.* Capacitors are added in capacitor case at the four-kilovolt network supply busses without changing the network design; hence, there is no difference in margin between the two cases.

5a. *13.8-Kv Consumer Fed From 33 Kv.* Additional transformer capacity was added for a 50 per cent load increase such that, with the addition of fans, a

Table I. Types of Feeders, Feeder Loads, and Distribution of Load Among Substations

Feeder Number	Feeder Type	Number at This Station	Load of This Type at This Substation								
			Present			Future					
						Without Capacitors			With Capacitors		
			Kilo-watts	Kilo-vars	Power Factor	Kilo-watts	Kilo-vars	Power Factor	Kilo-watts	Kilo-vars	Power Factor
Substation A											
1....	Residential	6	6,000	2,890	.091	10,900	5,370	.0896	10,870	2,044	.0985
2....	Commercial	2	1,988	1,496	.080	3,620	2,760	.0795	3,600	1,740	.090
3....	Industrial	3	3,030	2,610	.0758	4,490	3,370	.080	4,370	1,210	.0975
4....	Commercial network	0									
5a....	Industrial HTP**	2	24,880	21,560	.0756	39,800	34,500	.0755	39,000	18,300	.0895
5b....	Industrial HTP	0									
6....	Industrial HTP	1	13,970	12,190	.0753	21,200	18,300	.0755	20,900	9,900	.0904
Total.....			49,868	40,746	.0774	80,010	64,300	.0778	78,740	35,396	.0914
Substation B											
1....	Residential	12	12,020	5,860	.0898	21,800	11,200	.089	21,900	4,008	.0903
2....	Commercial	2	2,018	1,506	.030	3,590	2,710	.0798	3,600	1,760	.0897
3....	Industrial	24	23,840	20,500	.0758	36,300	27,000	.0802	36,000	11,800	.095
4....	Commercial network	15/24*	14,960	11,490	.0793	26,600	19,700	.0803	26,400	12,800	.090
5a....	Industrial HTP	0									
5b....	Industrial HTP	0									
6....	Industrial HTP	0									
Total.....			52,838	39,356	.0802	88,290	60,610	.0823	87,900	30,268	.0945
Substation C											
1....	Residential	12	12,320	6,060	.0896	22,100	10,800	.0897	21,900	4,208	.090
2....	Commercial	3	2,992	2,239	.080	5,600	4,000	.0808	5,470	2,570	.0904
3....	Industrial	0									
4....	Commercial network	0									
5a....	Industrial HTP	0									
5b....	Industrial HTP	2	26,080	22,960	.075	39,000	34,500	.0749	38,900	18,800	.090
6....	Industrial HTP	1	13,960	11,890	.0761	21,200	18,000	.0762	21,000	10,200	.090
Total.....			55,352	43,149	.0788	87,800	67,300	.0795	87,270	35,678	.0927

*Number of feeders with future loads.

**HTP stands for "high-tension (voltage) power."

vision would be made for an added load of 1,700 kva above the 1,000-kva increase.

3. *Industrial Feeder.* Voltage drop limits load on this type feeder. A regulator of proper ampere capacity for future load is installed when the load grows. The regulator rating is the limiting factor for further growth. Similarly, only enough capacitors are added in the capac-

100 per cent load increase could be taken on the basis of one line and one transformer out; 2,600 kva of capacitors could be added in the capacitor case with an emergency (one line and transformer out) full-load voltage drop of 12 per cent, but, in the no-capacitor case, emergency operation at 100 per cent load increase would result in a current through the

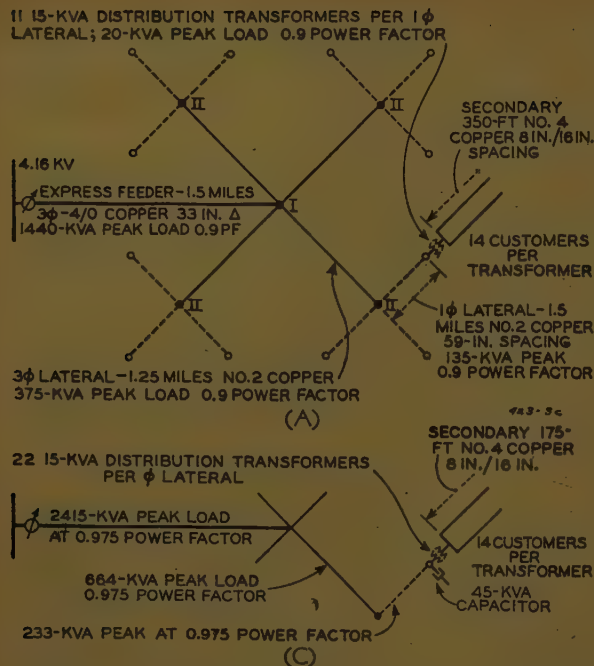


Figure 3. Residential feeder—type 1

single line of about 600 amperes with a 13.6 per cent voltage drop.

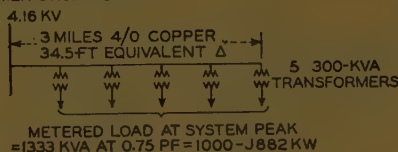
5b. 13.8-Kv Consumer Fed From 13.8 Kv. Voltage drop under emergency condition of one circuit out with future load is considered about maximum permissible and nearly the same for either case; hence, there is no room for increased loads either way without additional investment.

6. 33-Kv Consumer Fed From 33 Kv. No change to this feeder was necessary for it to carry the future load, but for the capacitor case a bank was added arbi-

trarily at the end of the feeder because of the large load kilovar requirement. This would permit about 8,800 kva of load at the original power factor to be added after future load arrived in the capacitor case, but none could be added in the no-

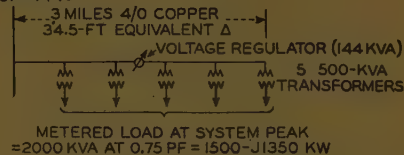
trarily at the end of the feeder because of the large load kilovar requirement. This would permit about 8,800 kva of load at the original power factor to be added after future load arrived in the capacitor case, but none could be added in the no-

FIRST TO LAST TRANSFORMER DROP=10.6%



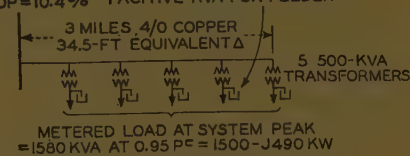
(A). Present

UNREGULATED DROP=14%

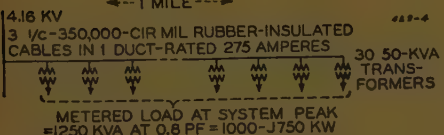


(B). Future—no capacitors

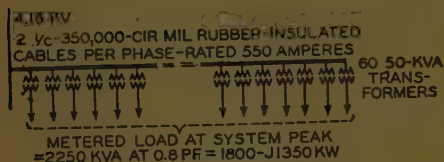
TOTAL OF APPROXIMATELY 830-CAPACITIVE KVA FOR FEEDER DROP=10.4%



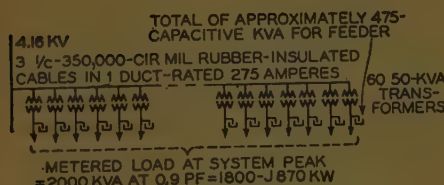
(C). Future—with capacitors



(A). Present



(B). Future—no capacitors



(C). Future—with capacitors

Figure 4. Commercial feeder, 4,160 volts—type 2

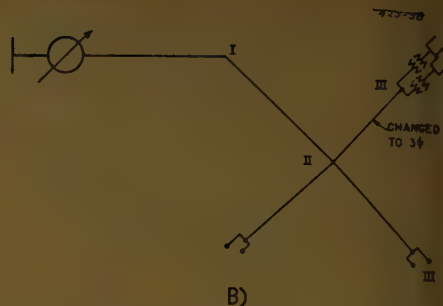
Figure 5. Industrial feeder, 4,160 volts—type 3

(A). Present
Voltage drops at feeder peak:
Secondary three per cent
Distribution transformer 3.2 per cent
One-phase lateral 3.9 per cent
Three-phase lateral 2.9 per cent
Express section 6.8 per cent
* Regulator compensates for these

Type 1 feeder. Present diversified peak at system peak 1,110 kva at 0.9 power factor = 1,000-j483 kw (neglecting losses)

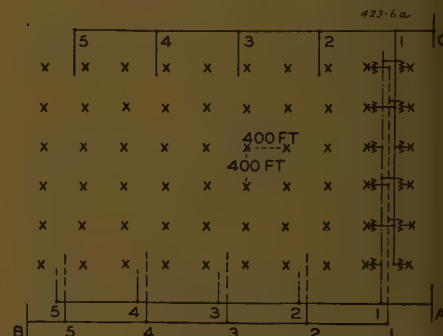
(C). Future with capacitors. Otherwise same as present
Voltage drops (at feeder peak)
Secondary 1.5 per cent
Distribution transformer 3.2 per cent
One-phase lateral 5.3 per cent (7.3-2 due capacitor)
Three-phase lateral 5.5 per cent *
Express section 12.3 per cent
* Regulator compensates for these

Type 1 feeder future diversified load at system peak=1,830 kva at 0.985 power factor=1,800-j316 kw (neglecting losses)

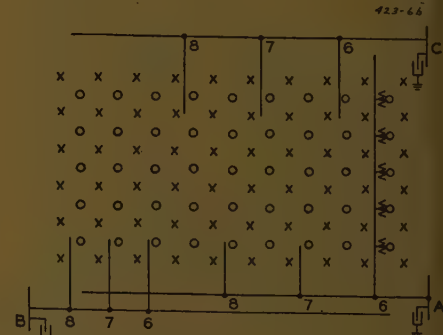


(B). Future without capacitors. Otherwise same as present

Drops (at feeder peak):
Secondary 1.5 per cent
Distribution transformer 3.2 per cent
Three-phase lateral II-III 1.3 per cent
Three-phase lateral I-II 5.5 per cent *
Express section 12.3 per cent
† Type 1 feeder future diversified load at system peak=2,010 kva at 0.9 power factor = 1,800-j876 kw (neglecting losses)



(a). Present—15 primary (4 kv) feeders—three-conductor 350,000 circular-mil cable average metered feeder load at system peak = 1,250 kva at 0.8 power factor. x indicates feed-in point to secondary network through 500-kva 4,160/120/208-volt transformer. Secondary grid uses two 250,000-circular-mil single-conductor cables per phase



(b). Future with and without capacitors shows added feeders only. Add nine three-conductor 350,000-circular-mil feeders. Average load of added feeders = 1,575 kva at 0.8 power factor. o indicates added feed-in points to added network through 500-kva 4,160/120/208-volt transformer. For with-capacitor case add 2,340 capacitive kilovolt-amperes at each of the three 4,160-volt supply busses, A, B, and C

Figure 6. Commercial network—type 4

Table II. Summary of Physical Changes in Feeder Circuits and Their Estimated Installed Costs to Handle Future Loads

Feeder Number	Feeder Type	Total Number This Type	Changes to Feeder Without Capacitors	Cost (Dollars)	Changes to Feeder With Capacitors	Cost (Dollars)	Total Cost (Thousands of Dollars)	
							Without Capacitors	With Capacitors
1.....	Residential	30	1. Split the secondary runs 2. Add 132 15-kva 2,400/120-240-volt transformers 3. Change 18 miles of one-phase lateral to three-phase and reconnect half or original transformers 4. Add 2,880 kva, 10 per cent induction regulator	24,000 10,500 10,000	1. Split the secondary runs 2. Same as for without capacitors 3. Add 540-kva outdoor distribution capacitors in 45-kva banks with hangers and one cutout per bank 4. Same as for without capacitors	24,000 2,300 10,000	1,335	1,089
2.....	Commercial	7	1. Add one single-conductor 350,000-circular mil varnished-cambric lead-covered cable per phase in existing one-mile duct 2. Add 30 50-kva 4,160/120-208 volt transformer with cutout	10,400 11,500	1. Add 498 kva of 7.5 kva 230 volts at 208-volt capacitor units in nine banks of nine units each with cutouts 2. Add 30 50-kva transformers	9,300 11,500	153.3	145.6
3.....	Industrial	27	1. Add 1,400 kva 10 per cent induction regulator	5,500	1. Add 900 kva of outdoor capacitors in 180-kva banks with hangers and cutouts	5,000	148.5	135
4.....	Commercial network	15 present 24 future	1. Add nine 3-conductor 350,000-circular mil cable feeders 2,000 feet long in new ducts 2. Add 45 500-kva network transformers and protectors and vaults	60,300 517,500	1. Same as without capacitors 2. Same as without capacitors 3. Add three banks of 2,340 kva of capacitors in housed racks at low side (1,460 volts) of feeder transformers with breakers	60,300 517,500 46,000	577.8	623.8
5a.....	13.8-kv customer fed by 6-mile 33-kv line	2	1. Add two 10-megavolt-ampere 33/13.8-kv transformers, including installation and station additions	44,000	1. Add two 7.5 megavolt-ampere 33/13.8-kv transformers, including installation and station additions 2. Add three 2,520-kva capacitor banks	35,000 49,600	88	169.2
5b.....	13.8-kv customer fed by 5-mile 13.8-kv lines	2	1. Add one 5-mile, 250,000 circular mil copper 13.8-kv line 2. Add two 1,000,000-kva 15-kv circuit breakers, including station additions	26,500 22,000	1. Add three 2,520-kva capacitor banks	49,600		
6.....	33-kv customer fed by 6-mile 33-kv lines	2			1. Add 8,280-kva capacitor bank	54,300	86	99.2
							2,388.6	2,370.4

capacitor case because of voltage drop and conductor thermal limitations.

It may be noted that for feeder type 2 the no-capacitor case shows the larger margin, whereas in type 6 the reverse is true. Also a more favorable emergency operating condition obtains under ultimate load conditions for feeder type 5a for the capacitor case than for the no-capacitor case.

Summary of Results

SYSTEM INVESTMENTS TO PROVIDE FOR LOAD GROWTH

In going from the present to the future system it was necessary to add the same amount of generating capacity at stations B and C with either method of pro-

viding for load growth. In view of this, the cost of the plant additions was not included in the comparison. This addition was one 25-megawatt unit at substation B and two 25 megawatt units at substation C.

The installed cost of changes to the feeders, substations, and subtransmission facilities to carry future loads with and without capacitors is itemized in Tables II and III. It is realized that the costs selected may differ considerably from those which would obtain on specific actual systems because of local conditions, but it is believed that the costs chosen are representative. A brief over-all summary of the investment results may be found in Table IV.

It is again emphasized that the major

gains indicated in Table IV appear in parts of the system other than the feeders because of the principle of system design adopted. Small substations with relatively short feeders are the general principles involved. This has generally been called the unit-substation or load-center type of distribution. This principle results in a relatively efficient distribution system with fewer of the properties usually conducive to capacitor gains, and, as seen, any substantial benefit must necessarily appear elsewhere in the system. The loss data given in the following section further indicate the high efficiency of this system in relation to the average actual system being operated. The loss at time of peak for the future case without capacitors is only

Table III. Summary of Physical Changes to Transmission Facilities and Estimated Installed Costs

Changes If Capacitors Are Not Used	Cost (Dollars)	Changes If Capacitors Are Used	Cost (Dollars)
1. Add 25 megavolt-ampere synchronous condenser, transformer, and circuit breaker....	212,000	Add 12 2,500-kva 33/4.16-kv transformers....	102,000
2. Add fans to two 3,750-kva transformers for 5,000 kva at 950..	1,900	Add 5 2,500-kva 13.8/4.16-kv transformers.....	37,500
3. Add six 2,500-kva 33/4.16-kv transformers.....	51,000		
4. Add six 5,000-kva 33/4.16-kv transformers.....	78,000		
5. Add fans to three 5,000-kva units for 6,250 kva at 1,100.....	3,300		
6. Add five 2,500-kva 13.8/4.16-kv transformers....	37,500		
Total.....	383,700	Total.....	139,500

0.13 per unit. Hence, one should not conclude too hastily that the gains (as to magnitude and location) obtained in this system through a general kilovar program will apply to his particular system. Power systems having the more usual type of distribution, that is, longer feeders, will show comparatively greater benefit to the distribution system itself from the application of capacitors thereto.

SYSTEM LOSSES

Table V summarizes the metered and generated loads and losses for the various cases.

The difference in load or metered kilovars between the capacitor and no-capacitor cases represents the kilovars of capacitors employed on the feeders and at distribution substations. This is 91,100 kva. The difference in kilovars supplied by generators for the two cases is 125,100 kilovars, so a kilovar loss of 34,000 obtains for the no-capacitor case.

The value of the reduction in losses of 7,900 kw and 34,000 kilovars, resulting from the load kilovars being supplied near the load, was not accounted for in the economic comparison because of the considerable variation in what is considered a fair cost for losses among engineers. At any given rate, either on a capitalized

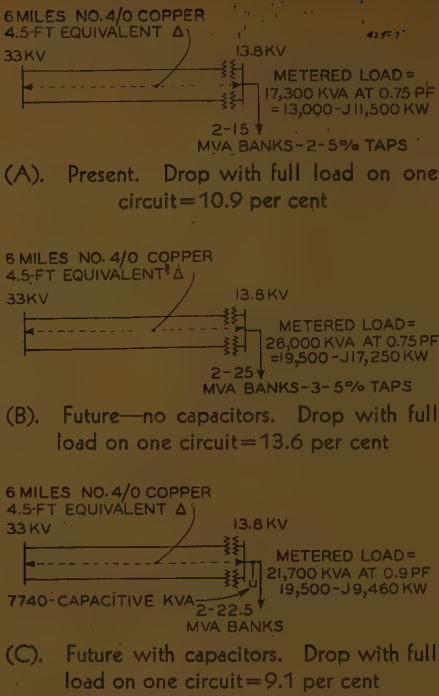


Figure 7. 13.8-kv industrial customer fed from 33 kv—type 5a

investment or energy charge basis, the power losses may, of course, be evaluated readily. Similarly, the reactive power losses may be charged for on a basis of system investment required to supply them, or simply in terms of the cost of capacitors or condensers of ratings equal to the difference in losses. In any event, this difference in losses represents a difference in operating margins, and may be evaluated accordingly.

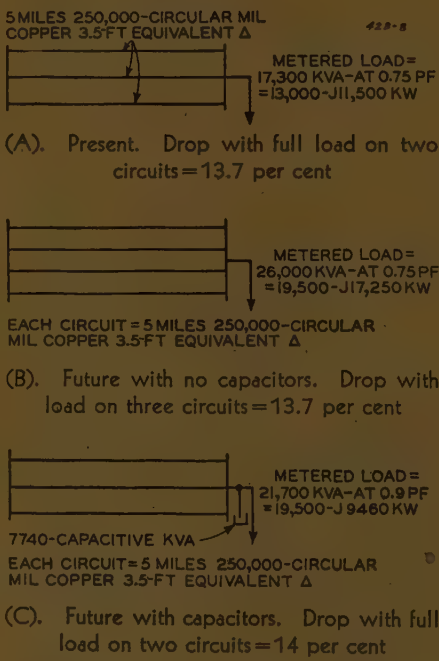


Figure 8. 13.8-kv industrial customer fed from 13.8 kv—type 5b

GENERATING-PLANT MARGINS—NORMAL AND EMERGENCY OPERATION

Table III shows no change in generating capacity, because, for the system studied, the future kilowatt requirements demanded the same number of generators at stations B and C whether or not distribution capacitors were used. Similarly, the hydroelectric plant capacity required would be the same, since economics and operating requirements normally tend toward practically unity-power-factor long-distance transmission. However, at substation A a larger synchronous condenser is needed for the no-capacitor case to supply the required kilovars to this load area.

The difference in kilovar burdens and system-loss requirements on steam-generating plants B and C, therefore, evidences itself in this study in greater margins for future growth and for emergency conditions. The evaluation of this is left to the reader, but actually it could have been, and normally would be, evaluated in terms of the cost of generator or kilovar supply capacity installed at the station. If the generators can carry added kilowatt load when their kilovar load is reduced, it could be measured in terms of generator capacity costs.

In future steam-station loads with no capacitors, normal margin is one machine (spinning reserve) of 25-j 18.75 megawatts. (The minus sign on reactive quantities represents magnetizing reactive kilovolt-amperes throughout this paper.)

In future steam-station loads with capacitors, normal margin is 31.7-j 61.9 megawatts, which includes the unit held in spinning reserve.

On this basis, if it is assumed that the boilers and steam-unit prime movers have sufficient capacity, the generators can supply the load requirements under low-water conditions with two hydroelectric

Table IV

Item	With Capacitors	Without Capacitors
Cost of changes to feeders for a 100,000-kw system load increase.....	\$2,370,400	\$2,388,600
Cost of changes to rest of system, exclusive of power plant for this load increase.....	\$139,500	\$383,700
Total cost, exclusive of power plant.....	\$2,509,900	\$2,772,300
Cost per kilowatt of added transmission- and distribution-system capacity.....	\$25.10	\$27.72

Table V. Summary of Metered and Generator Loads

Station	Megawatts	Reactive Megavolt- Amperes
Present me- tered loads.....	A..... 49.87.....	40.75
	B..... 52.84.....	39.36
	C..... 55.35.....	43.24
Total.....	158.06.....	123.35
Present gener- ation.....	A..... 58.0.....	8.2
	B..... 57.5.....	52.0
	C..... 58.8.....	46.0
Condenser.....		51.6
Total.....	174.3.....	157.7
	158.1.....	123.4
Losses....	16.2.....	34.3
Future with- out capaci- tors loads.....	A..... 80.01.....	64.3
	B..... 88.29.....	60.6
	C..... 87.9.....	67.3
Total.....	256.1.....	192.2
Generation.....	A..... 91.5.....	4.9
	B..... 100.0.....	88.8
	C..... 98.0.....	82.0
Condenser.....		76.0
Total.....	289.5.....	251.7
	256.1.....	192.2
Losses....	33.4.....	59.5
Future with capacitors loads.....	A..... 78.7.....	34.19
	B..... 87.9.....	31.27
	C..... 87.3.....	35.68
Total.....	254.0.....	101.14
Generation.....	A..... 86.2.....	-10.9
	B..... 97.6.....	44.9
	C..... 95.7.....	45.8
Condenser.....		46.8
Total.....	279.5.....	126.6
	254.0.....	101.1
Losses without capacitors.....	25.5.....	25.5
Losses with capacitors.....	33.4.....	59.5
Reduction in losses with ca- pacitors.....	25.5.....	25.5
Metered kilovar load without capaci- tors (future).....	7.9.....	34.0
Metered kilovar load with capacitors (future).....		192.2
		101.1
Capacitor kilovolt-amperes added.....		91.1

units off if capacitors are not used, and with three hydroelectric units off if they are used. This is seen readily from the data in Figure 11 and is an example of how the generating-plant margins may be evaluated in terms of operating conditions.

Capacitors as a Stepping Stone in System Growth

The analysis reported in this paper was made on the basis of considering the cost of an addition to a system, as though its load grew 67 per cent, and the changes were almost overnight. No account was taken of the effects of providing for this ultimate increase in steps, somewhat ahead of an increment of load growth. It was assumed that this effect would be

Table VI. Δ Kilovars Per Δ Kilovolt-Ampere Per 0.05 Step in Power Factor

Δ Power Factor	Δ Kilovars Per	Δ Kilovolt-Ampere
1.0 - 0.95.....	6.2	
0.95 - 0.90.....	2.68	
0.90 - 0.85.....	2.06	
0.85 - 0.80.....	1.8	
0.80 - 0.75.....	1.59	

The increase in kilovar capacity per kilovolt-ampere capacity in going from 0.95 to 0.90 power factor is 2.68.

Table VII. Generator Kilovolt-Amperes and Power Factor for Various Line Reactance and Load Values for Constant Kilowatts

Load Power Factor	Circuit Reactance = 0.20		Circuit Reactance = 0.30	
	Gen- erator Kilovolt- Amperes	Gen- erator Power Factor	Gen- erator Kilovolt- Amperes	Gen- erator Power Factor
1.0.....	1.02.....	0.981.....	1.042.....	0.96
0.95.....	1.13.....	0.886.....	1.18.....	0.848
0.90.....	1.21.....	0.828.....	1.27.....	0.788
0.85.....	1.29.....	0.773.....	1.36.....	0.736
0.80.....	1.39.....	0.72.....	1.45.....	0.69
0.75.....	1.47.....	0.68.....	1.54.....	0.648

the same whether the capacitor or no-capacitor method were used in providing for the load increment. Obviously, this would be difficult of evaluation, unless a knowledge of the load growth or trend with time were available. Such knowledge is, however, available on actual systems and should be made use of for the purpose described.

Actually, if this effect were evaluated, it would favor the use of capacitors, since they can be added in smaller quantities and follow the load growth more closely than regulators, transformers, lines, and cable circuits necessarily are able to do. Thus, there would be at any time somewhat less unused capacity lying idle waiting for the load to grow and use it up.

Another way of saying this is that the capacitor postpones the investment until such time as the larger equipment can be added justifiably, and it is in this way that capacitors may come to be used more in meeting system growth. Their high re-use value and great flexibility will permit them to be used on one part of a system for a time until it is enlarged and then to be moved elsewhere to repeat the process of following the load growth there.

IMPORTANCE OF COMPLETE SYSTEM VIEWPOINT

As were pointed out in the opening paragraphs of this paper, there are cases where, to meet a single requirement, and with alternate equipment available, the use of capacitors would not be justified. A study of the detailed feeder cost com-

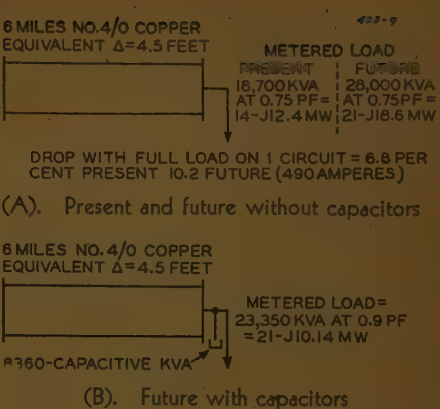


Figure 9. 33-kv customer fed from 33 kv—type 6

parisons will show examples of this. There are two cases (feeders 4 and 6) where capacitors were not needed on the feeders themselves, but they were added at this location, as it was the logical place for kilovar production in the co-ordinated program.

This fact emphasizes the need for definite correlation in power-system design groups between those responsible for distribution-system design and those who design and operate the subtransmission, transmission, and generation portions of the system—an over-all viewpoint taken by all of these groups will make for added system economy.

How Far Should Load Kilovars Be Transmitted?

In systems where the loads are relatively near the generating plants, the question may be raised concerning the wisdom of supplying kilovars with capacitors instead of with the generators. The analysis reported in this paper answers

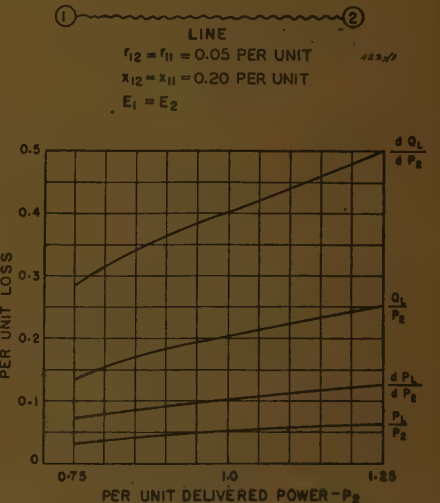


Figure 10. Relation between incremental and actual power losses over a circuit. Voltages maintained equal at points 1 and 2 by kilovar control

this question for a particular system in detail. The following discussion presents a few additional notes from which a quick picture of the general problem may be obtained.

As a basis for discussion and comparison, the data in Table VI are first presented. These figures give the incremental kilovar capacity per kilovolt-ampere required to be built into equipment such as cables, transformers, and generators at constant kilowatt load for certain finite steps in power factor.

On the basis that equipment costs are somewhat proportional to its kilovolt-ampere rating, these figures indicate the degree to which kilovar capacity becomes increasingly expensive at the lower power factors. This is another way of saying the well-known fact that power-factor improvement tends to become uneconomical at the higher power factors.

WHEN GENERATOR OUTPUT IS
STEPPED UP THROUGH TRANSFORMERS

A unity power-factor load supplied through a 0.30 per unit reactance requires that 1.0 kw +0.30 kilovar be supplied by the generator, corresponding to 0.96 power factor. Following this reasoning, for several load power factors and two values of reactance, gives the data in Table VII.

Since it takes only two transformers to total approximately 0.20 per unit reactance, 0.30 per unit would not be uncommon for the total of a subtransmission circuit where line loading is generally relatively heavy. And with 0.30 per unit it is required that the load power factor be 0.95 if the generator power factor is to be approximately 0.85. Thus, line I²X losses are not small and are to be respected.

WHEN LOAD IS SUPPLIED AT
GENERATOR VOLTAGE

Under this condition for the case of overhead lines, one cannot readily make

Table VIII. Dollars Per Kilovar Investment Chargeable Per 0.05 Step in Power Factor for Three Mileages

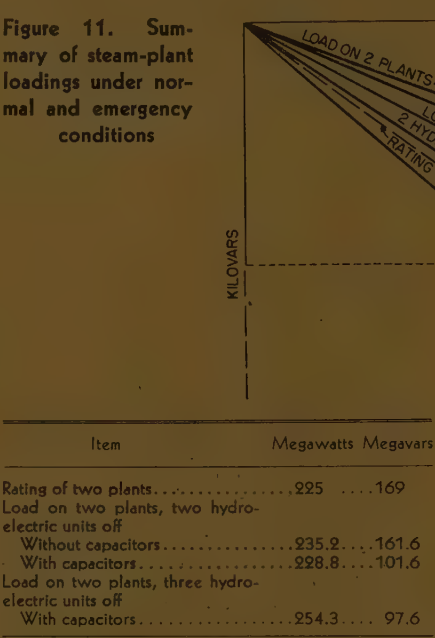
Δ Power Factor	4 Miles	8 Miles	12 Miles
1.0 -0.95.....	1.21.....	2.42.....	3.63
0.95-0.9	3.08.....	6.6	9.24
0.9 -0.85.....	4.13.....	8.26.....	12.39
0.85-0.8	5.2	10.4	15.6
0.80-0.75.....	6.22.....	12.4	18.66

At 0.95 power factor the investment chargeable per kilovar capacity for eight miles is \$2.42, and the charge for the additional kilovar capacity required in going from 0.95 to 0.9 power factor is \$6.18.

an analysis in view of the difficulty of establishing the rating and the effect of power factor on the rating of such a line. Purely on the basis of line reactance, however, the data in Table VII are applicable.

Cable circuits, where thermal capacity is the limiting factor, may be approached as follows. A conservative figure for 3/C cable, being operated at the most economical loading, is approximately \$1.45 per kilovolt-ampere-mile. An additional charge of about \$0.45 per kilovolt-ampere-mile for ducts brings the figure to \$1.9 per kilovolt-ampere-mile total. When only these figures are used, and the costs of terminal equipment, such as generators are ignored, the data in Table VIII can

Figure 11. Summary of steam-plant loadings under normal and emergency conditions



be determined readily. These figures give the incremental cost chargeable to incremental kilovar per 0.05 step in power factor for three cable mileages. For other cable lengths costs at a particular power-factor increment are directly proportional to length.

These figures give an indication as to how far loads at various power factors can be supplied by cables to balance the investment necessary in capacitors to furnish the incremental kilovars, namely, approximately \$5 or \$6 per kilovar. For instance, from the table, at four miles, the load power factor should be improved to approximately 0.85, because below this the incremental kilovar costs favor capacitors, and at approximately eight miles the power factor should be 0.95, which somewhat indicates the limit of kilovar transmission through cable.

The kilovolt-ampere loadings of the cables in this discussion correspond ap-

proximately to those whose I²X losses will consume the cable charging kilovolt-amperes. Thus, the cable line-charging kilovolt-ampere is not ignored.

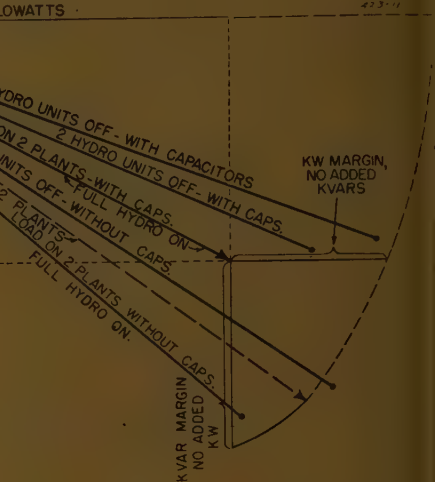
Appendix

Incremental Kilovar and Kilowatt Losses

CASE I. LOAD VOLTAGE MAINTAINED BY RAISING SENDING-END VOLTAGE

This case characterizes a circuit with a regulator or load-ratio control at the substation for maintaining voltage in a remote load area.

$$P_2 = \frac{e_2^2 \cos \theta_2}{Z_2} = \text{load kilowatts} \tag{1}$$



where Z_2 =magnitude of load impedance and θ_2 =load power factor. Neglecting line-charging current

$$P_L = \frac{e_2^2 Z_1}{Z_2^2} = \text{power loss in } Z_1, \text{ the line impedance} \tag{2}$$

From 1

$$Z_2 = \frac{e_2 \cos \theta_2}{P_2}$$

so

$$P_L = \frac{P_2^2 Z_1}{e_2^2 \cos^2 \theta_2} \tag{3}$$

and the incremental loss with respect to load kilowatts is

$$\frac{dP_L}{dP_2} = \frac{2P_2 Z_1}{e_2^2 \cos^2 \theta_2} \tag{4}$$

From 3

$$\frac{P_L}{P_2} = \frac{P_2 Z_1}{e_2^2 \cos^2 \theta_2} = \text{actual power loss in per unit of load kilowatts} \tag{5}$$

If equation 4 is divided by equation 5, the ratio of the incremental to the actual power loss is found to be 2, a well-known result.

This analysis also applies for the load-loss component of transformer and machine losses.

This case characterizes a subtransmission or transmission circuit utilizing kilovar sources, such as synchronous condensers, at either end for controlling voltage.

The well-known power equations for such a circuit with power flowing from point 1 to point 2 are

$$P_1 = \frac{E_1^2}{Z_{11}} \sin \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \quad (6)$$

$$P_2 = \frac{E_2^2}{Z_{22}} \sin \alpha_{22} - \frac{E_1 E_2}{Z_{12}} \sin (\delta_{12} + \alpha_{12}) \quad (7)$$

$$Q_1 = \frac{-E_1^2}{Z_{11}} \cos \alpha_{11} + \frac{E_1 E_2}{Z_{12}} \cos (\delta_{12} - \alpha_{12}) \quad (8)$$

$$Q_2 = \frac{-E_2^2}{Z_{22}} \cos \alpha_{22} + \frac{E_1 E_2}{Z_{12}} \cos (\delta_{12} + \alpha_{12}) \quad (9)$$

P_1, P_2 = real power passing points 1 and 2
 Q_1, Q_2 = reactive power passing points 1 and 2

Z_{12} = ratio of voltage at 1 to current at 2 when 2 is grounded

Z_{11} = ratio of voltage at 1 to current at 1 with 2 grounded

Z_{22} = ratio of voltage at 2 to current at 2 with 1 grounded

$$\alpha_{11} = \tan^{-1} \frac{r_{11}}{X_{11}} \quad \alpha_{22} = \tan^{-1} \frac{r_{22}}{X_{22}}$$

δ_{12} = angle between voltage E_1 and E_2

$$\alpha_{12} = \tan^{-1} \frac{r_{12}}{X_{12}}$$

For a line section with no intermediate loads $Z_{11} = Z_{22}$, and when equal voltages held at either end are assumed, the equations for power loss are

$$P_L = \frac{2E^2}{Z_{11}} \sin \alpha_{11} - \frac{2E^2}{Z_{12}} \sin \alpha_{12} \cos \delta_{12} \quad (10)$$

$$Q_L = \frac{-2E^2}{Z_{11}} \cos \alpha_{11} + \frac{2E^2}{Z_{12}} \cos \alpha_{12} \cos \delta_{12} \quad (11)$$

It is desired to find the incremental power losses with respect to the receiving power P_2 .

Solving for $\cos \delta_{12}$ in equation 7, there is

$$\cos \delta_{12} = \cos (\alpha_{12} + \psi) \quad (12)$$

$$\psi = \tan^{-1} \frac{\left(P_2 - \frac{E_1^2 \sin \alpha_{11}}{Z_{11}} \right)}{\left[\frac{E^2}{Z_{12}} - \left(P_2 - \frac{E^2}{Z_{11}} \sin \alpha_{11} \right)^2 \right]^{1/2}}$$

Substitute equation 12 in equations 10 and 11 and differentiate to get

$$\frac{dP_L}{dP_2} = 1 - \frac{\cos (\alpha_{12} + \psi)}{\cos \psi} \quad (13)$$

and

$$\frac{dQ_L}{dP_2} = - \left[\tan \psi + \frac{\sin (\alpha_{12} + \psi)}{\cos \psi} \right]$$

Equations 13 and 14 give the incremental power losses with respect to the delivered power, and, if equations 10 and 11 are divided by P_2 , the actual power losses in per unit of delivered power are obtained. A

A Multiplied-Deflection A-C Potentiometer

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ASSOCIATE AIEE

THE power required for the operation of an indicating instrument frequently makes its use prohibitive because of the disturbing effect it has on the circuit being measured. If the measurement is in a d-c circuit, the difficulty is overcome readily by using a d-c potentiometer. In a-c measurements, the indicating instruments have a much greater disturbing effect on the circuit, and the use of an a-c potentiometer is very desirable. Furthermore, a-c potentiometers are very useful for measuring power in circuits where the power is too small to be measured with a dynamometer wattmeter.

Most a-c potentiometers have the disadvantage of being too complicated to be used by any but a skilled operator. They have the further disadvantage that they usually are not offered for sale as portable all-purpose instruments. Instead, a special laboratory assembly is used for each task to be performed. One of these arrangements utilizes a calibrated phase shifter. A means of phase detection must be used so that the scale on the phase shifter can be set on the proper value. In addition, the potentiometer current must be standardized for magnitude, and the standardizing process is somewhat more complicated with alternating current than it is in the case of the d-c potentiometer. In another form of the laboratory arrangement, a mutual inductor is used to produce the quadrature component of potentiometer voltage. In this case, the phase angle between two currents must be adjusted to zero, and the magnitude of the potentiometer current must be standardized.

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The multiplied-deflection a-c potentiometer eliminates all of these difficulties and makes the operation so simple that an inexperienced operator can make accurate measurements with ease. The instrument is portable and suitable for field work. Very little skill is necessary to make the null balance, and the operator scarcely can make a mistake in determining the results, provided he reads the three indicating instruments (voltmeter, ammeter, and wattmeter) correctly.

The designation *multiplied deflection* was adopted because indicating instruments are used, and their deflections are convenient multiples of the measured quantity. For example, 100 millivolts may be read as 100 volts on a 150-volt indicating instrument, but the reading then is divided by 1,000, as indicated on the potentiometer ratio dial. This potentiometer was developed for the purpose of measuring the impedance and power consumption of circuit elements having a fraction of an ohm of impedance. The current coil of a watt-hour meter was the first circuit element studied, and the results were so highly satisfactory that the instrument was rebuilt with a circuit-changing switch so that it also could be used for measuring high impedances. With this circuit, the impedance and core loss of a doorbell transformer or small radio transformer can be measured easily. High impedances up into the megohms are measured as readily as low impedances, and the circuit may be guarded from leakage in the customary manner, if it is desirable to do so. Numerous other applications become apparent, and some of these will be described later.

Figure 1 shows the scheme used for the measurement of a low-impedance circuit element designated as Z_x . The four terminals (two for current and two for

simple relation for the ratio of the incremental to the actual power loss, as was obtained in case 1, is not evident; so, a numerical case is given, as in Figure 10, to enable a concept to be obtained as to their relative magnitudes. From the data in Figure 10 it is seen that the ratio of the incremental to the actual losses is approxi-

mately 2 for a large range of values of P_1 . This fact, coupled with the factor 2 obtained in case 1, strongly tempts one to draw the general conclusion that no matter how a circuit is operated with respect to holding voltages, the ratio of the incremental to actual power losses in regions of practical operation is always approximately 2.

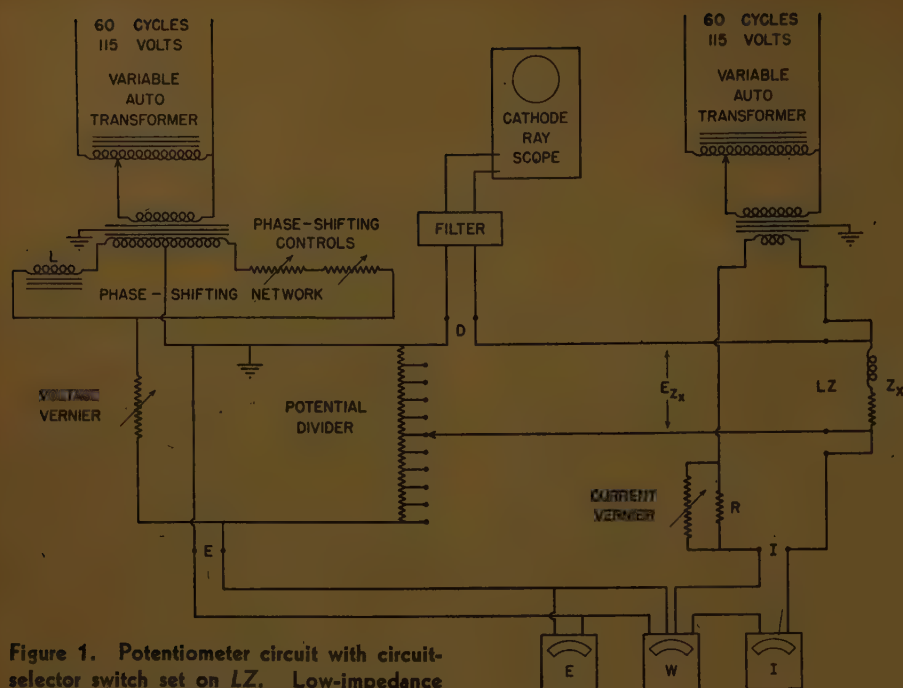


Figure 1. Potentiometer circuit with circuit-selector switch set on LZ. Low-impedance measurements

potential) of Z_x are connected to the LZ posts. In the upper right-hand part of the figure an adjustable-ratio autotransformer and the voltage-vernier rheostat. Major and vernier phase-shifting rheostats are provided as indicated. A potential divider is used in this circuit in very much the same manner as a volt box is used with a d-c potentiometer. The resistors that make up the potential divider are accurate to one tenth of one per cent and are noninductive.

justment is thus made negligible. The magnitude of the output voltage of the phase shifter is varied with the adjustable-ratio autotransformer and the voltage-vernier rheostat. Major and vernier phase-shifting rheostats are provided as indicated. A potential divider is used in this circuit in very much the same manner as a volt box is used with a d-c potentiometer. The resistors that make up the potential divider are accurate to one tenth of one per cent and are noninductive.

To obtain a null balance the current through the unknown impedance is first adjusted to the correct value. The voltage (left-hand) autotransformer is then adjusted, until a reading is obtained on the upper part of the voltmeter scale. A 150-volt range is very satisfactory for the voltmeter. The potential divider is then adjusted, point by point, until its output voltage is approximately equal to E_{zx} . Exact balance is obtained by adjusting the voltage in both magnitude and phase position, until a zero indication is obtained on a null detector.

Any sensitive detector should be suitable for determining the point of final balance. A cathode-ray oscillograph with a gain of 1,000 in the vertical amplifier is quite satisfactory. Since the oscillograph is rather cumbersome, an electric-eye detector is more suitable for a portable potentiometer. Harmonics occurring in the voltage across Z_x are not balanced by the voltage from the potential divider. These harmonics are eliminated by the use of a filter. It will be shown later that this does not introduce any error.

When the balance has been obtained, the three indicating instruments and the potential-divider ratio N are observed. The voltmeter and wattmeter indications are then divided by N . The results are calculated from the usual formulas used with voltmeter, ammeter, and wattmeter data. Let E , I , and P indicate the instrument readings. Then

$$\begin{aligned} E_{zx} &= E/N \\ P_{zx} &= P/N \\ Z_x &= E/NI \\ R_{zx} &= P/NI^2 \\ \cos \theta &= P/EI = \text{power factor} \\ X_{zx} &= Z_x \sin \theta \end{aligned}$$

As an example of the use of these formulas, assume that the following data are obtained

$$\begin{aligned} E &= 90 \text{ volts} \\ I &= 5 \text{ amperes} \\ P &= 200 \text{ watts} \\ N &= 2,000 \end{aligned}$$

Then $E_{zx} = 90/2,000$ volts or 45 millivolts

$$P_{zx} = 200/2,000 \text{ or } 0.1 \text{ watt}$$

$$Z_x = \frac{0.045}{5} = 0.009 \text{ ohm}$$

$$R_{zx} = \frac{0.1}{25} = 0.004 \text{ ohm}$$

$$\cos \theta = \frac{200}{5 \times 90} = 0.444$$

$$X_{zx} = 0.00807 \text{ ohm}$$

There is no correction for the potential coil or current coil of the wattmeter, because the potential is supplied from a circuit that is independent of the current circuit.

With reference to Figure 3, it may be seen that a switch is provided to change the circuits in the instrument. When the switch is set in the LZ position, the circuit shown in Figure 1 is obtained. Figure 2 shows the circuit that results when the switch is set in the HZ position. In Figure 2 the potential divider is reconnected so that it becomes a current shunt. The unknown impedance is then attached to the HZ terminals and is, therefore, connected in series with the current shunt. A standard 0.2-ohm non-inductive resistor R_s is in series with the ammeter and wattmeter current coil, and the drop across R_s is compared with the drop across the current shunt.

In measuring a high impedance the voltage is adjusted to the value desired for the impedance at hand. Actually, the voltmeter reads the voltage across both Z_x and the current shunt. The error caused by this is negligible, since the current shunt is turned to the points of high resistance only when Z_x is exceedingly high. The current-shunt resistors

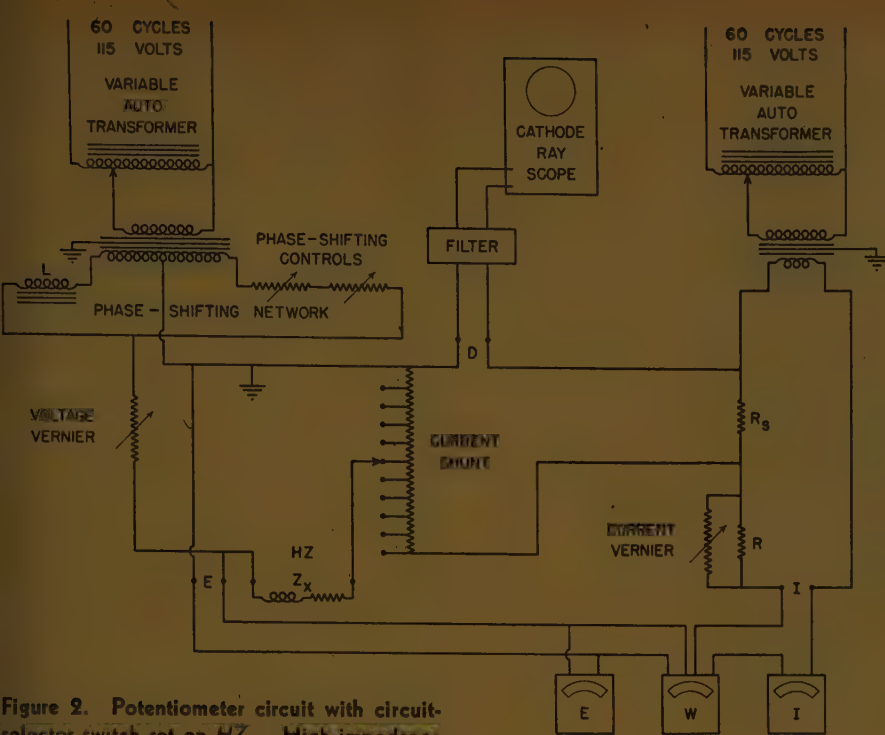


Figure 2. Potentiometer circuit with circuit-selector switch set on HZ. High-impedance measurements

are selected so that the error is less than 0.25 volt. The current through R_s is set at any convenient value, which causes the ammeter to read on the upper part of its scale. The current shunt is then adjusted until its voltage drop is equal approximately to the drop across R_s . Final null balance is obtained by means of the current vernier and the potential phase shifter.

The instruments used are the same as those used for measuring a low impedance, and none of the instrument connections are altered. The ratio n is the ratio of the current shunt resistance to the fixed resistor R_s . Two engraved scales are provided on the ratio dial, and care must be taken to read the correct scale. Let E , I , and P indicate the readings of the instrument

$$I_{Zx} = I/n$$

$$P_{Zx} = P/n$$

$$Z_x = En/I$$

$$R_{Zx} = Pn/I^2$$

$$\cos \theta = P/EI = \text{power factor}$$

$$X_{Zx} = Z_x \sin \theta$$

As an example of a high-impedance measurement, suppose that a small transformer is tested and the following data are obtained:

$$E = 115 \text{ volts}$$

$$I = 4.5 \text{ amperes}$$

$$P = 160 \text{ watts}$$

$$n = 1,000$$

$$I_{Zx} = 4.5/1,000 \text{ amperes or } 4.5 \text{ milliamperes}$$

$$P_{Zx} = 160/1,000 \text{ watts or } 160 \text{ milliwatts}$$

$$Z_x = 115,000/4.5 \text{ or } 25,600 \text{ ohms}$$

$$R_{Zx} = \frac{160,000}{20.2} \text{ or } 7,930 \text{ ohms}$$

$$\cos \theta = \frac{160}{115 \times 4.5} = 0.31$$

$$X_{Zx} = 25,600 \times 0.95 = 24,300 \text{ ohms}$$

In Figure 3 the two adjustable-ratio autotransformers are not shown. These are attached as auxiliary equipment. The ammeter and wattmeter are connected to the posts marked I . The voltmeter and wattmeter are connected to the posts marked E . High-impedance circuit elements are attached to the two posts marked HZ , and low-impedance circuit elements are attached to the four posts marked LZ . The detector is connected to the posts marked D . The ventilated compartment, mounted in the back, houses the phase-shifting network. Three fuses (upper center) protect the resistors in the current shunt when the circuit of Figure 2 is used. The fuses are inserted in such a way that the fuse resistance does not affect the calibration.

Miscellaneous Applications

To measure a low voltage it is necessary to connect it only across the two inner posts of the LZ terminals. The circuit selector is set on LZ , and the balance is made without switching on the current circuit. No current is drawn from the unknown potential at balance, and the voltage is determined by reading the voltmeter and dividing by the potential-divider ratio.

To calibrate a millivoltmeter when only a standard 150-volt voltmeter is avail-

able, the standard voltmeter is connected to the E posts of the potentiometer. The millivoltmeter may be operated from an independent source, and the values may be measured by connecting from the millivoltmeter to the inner posts of the LZ terminals.

To calibrate a milliammeter when only a standard five-ampere instrument is available, it is necessary only to insert a rheostat with the milliammeter in series across the HZ terminals and to connect the standard ammeter to the potentiometer-ammeter terminals.

To measure leading power-factor elements of either high or low impedance, or to measure the capacitance and power factor of a capacitor, it is necessary to make a change in the range of the phase shifter. As previously stated, the phase shifter covers a range somewhat greater than 120 degrees. If a three-phase supply is available, the left-hand autotransformer can be connected to either phase, and the entire 360-degree range may be utilized. The phase shifter in the potentiometer described covers the range from in phase to 120 degrees lagging when both autotransformers are connected to the same phase. If it is desirable to measure leading power-factor elements in a location where three-phase power is not available, the construction of the phase shifter should be altered so that the inductor L is replaced by a capacitor. The phase shifter will then cover the range from in phase to approximately 180 degrees leading. The output voltage of the phase shifter then should be filtered to eliminate any objectionable harmonics that are amplified by the capacitor.

The impedance and power loss due to leakage and dielectric hysteresis in lead-covered cables can be measured in the same manner as a capacitor. If it is desirable to guard the insulated ends of the cable, the guard wire should be attached to ground.

The application for which this instrument was originally designed is that of measuring the burden occurring on a current transformer in a metering installation. Since the potentiometer is portable, the burden may be measured at the site of the installation simply by disconnecting the current transformer. The transformer then may be removed and calibrated in the laboratory, if a duplicate burden is provided.

Sources of Error

Since the data on the multiplied-deflection potentiometer are obtained from indicating instruments, the entire pro-



Figure 3. Top panel view of the potentiometer, exclusive of adjustable-ratio transformers, instruments, and null detector

cedure is limited in accuracy to the accuracy of these instruments. If high-grade dynamometers are used, an overall accuracy of one quarter of one per cent can be obtained. Errors in the resistors used in the potentiometer are reduced so that they are negligible compared with the instrument errors. Insulation resistance within the potentiometer must be arranged carefully to prevent leakage across the *HZ* terminals. Since the high-impedance values sometimes run into the megohm range, the insulation resistance must be in the hundreds of megohms in order to realize maximum accuracy. If desirable, these leakage paths may all be eliminated by guarding in the conventional manner. All guards should be attached to ground.

It should be noted that the transformer in the current circuit is shielded and grounded. A similarly shielded transformer is incorporated in the phase-shifting network. This precaution is necessary in order to prevent capacitance currents from feeding through the potentiometer from one autotransformer to the other.

The most irritating question pertaining to the accuracy of the instrument has to do with the handling of harmonics. This problem is not peculiar to this particular potentiometer. In fact, the problem is not a matter of potentiometer accuracy, but a question of just what is meant by the impedance and power factor of an iron-core coil which generates harmonics when a sine wave of current is passed through it.

With reference to Figure 1, suppose that Z_x is an iron-core reactor. The current passed through it is of good wave form, because the resistor R is the chief impedance in the circuit. The voltage drop across Z_x probably will contain conspicuous harmonics. The voltage output from the voltage divider has a very good wave form. Thus, it may be seen that the output voltage from the voltage divider is adjusted actually to equal the fundamental component of voltage drop across Z_x , and the harmonics are eliminated by the filter. Under this condition, the result obtained by dividing the voltmeter reading by N is the rms value of the fundamental component

of the impedance drop, and not the rms value of the actual voltage drop. The value of impedance obtained by dividing this voltage drop by the ammeter reading is the fundamental component of impedance. It is interesting to note that the harmonics do not cause any doubt about the wattmeter accuracy, for, even if the harmonics were impressed across the potential coil of the wattmeter, there would be no harmonic current in the current coil, and the reading would be the same.

In Figure 2 suppose that Z_x is a small transformer, the core loss and exciting current of which are to be measured. In this case, the voltage across Z_x is of good wave form, but the current through Z_x will contain pronounced harmonics. When the potentiometer is balanced, the harmonics are again eliminated by the filter, and the value of current determined by the potentiometer is the rms value of the fundamental component of exciting current. The calculated impedance is the fundamental component of impedance. The divided wattmeter reading is the true value of power loss.

Operation at Higher Frequencies

The design of the multiplied-deflection potentiometer is made possible because the dynamometer wattmeter provides isolation between its potential coil and its current coil. Thus, the range of frequency is the same as that of a dynamometer wattmeter. This places the upper limit at about 1,000 cycles. A modified design, which utilizes a thermocouple wattmeter, is being studied, but this calls for major changes in the entire circuit design.

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Automatic Ticketing of Telephone Calls

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THERE has recently been placed in commercial service in the Bell System a new arrangement of telephone switching equipment designed to enable telephone users in a metropolitan area to dial for themselves their calls to nearby points instead of placing them with an operator. This added central-office equipment has the distinctive feature that it automatically prepares an individual printed ticket showing the information needed for charging for the call. The initial installation serves some 8,000 subscribers at Culver City, adjoining Los Angeles. It enables them to dial directly, in the same way as local calls, their calls to various points within the Los Angeles metropolitan area and thereby enlarges the scope of their dial service, with its attendant advantages in speed and convenience.

This paper describes briefly the functions and design of this form of automatic ticketing, which is designed for use with central-office switching equipment of the step-by-step type. In addition to ascertaining and printing the information needed for billing, the equipment also incorporates features for routing calls economically through the trunking network. The plan in some respects resembles and in other respects differs from automatic ticketing arrangements developed abroad and used commercially in several networks in Belgium prior to the war.¹

Present Methods of Handling Calls

Before describing the operation of the new system it may be well to review the present methods of handling telephone calls in metropolitan areas. The methods outlined below are, in essence, those used

at Los Angeles, the largest city in the United States employing step-by-step equipment.

Figure 1 is an idealized map of a metropolitan area. The heavy circle represents the boundary of the city exchange; in general, it includes the closely built-up business, industrial, and residential regions, but is not identical with the municipal boundary. The city exchange may be divided into zones, shown dotted, used for determining toll rates for calls between various parts of the city and the several suburbs, and in some cases be-



Figure 1. Idealized map of metropolitan area

tween the zones of the city itself. Surrounding the city are nearby suburban exchanges designated A to H; these may be well-separated communities, or may practically merge with each other or with the city. Farther out are other suburbs designated M to T. While such geographical regularity is not to be found in any actual city, this picture will serve to illustrate principles.

The lines serving telephone subscribers terminate in central-office buildings located in the various exchanges. The city exchange has a number of buildings, some of which may house as many as five or six central-office switching units, the con-

ventional central office having a capacity of 10,000 subscriber numbers. A suburban exchange may have one or several buildings each with one or a few central offices.

The switching plan for completing calls between subscribers in such a metropolitan area may be visualized by considering calls originating in a specific central office, for example, one in the suburban exchange designated F. Figure 2 shows in simplified form the switching plan of such an office. The subscriber lines are connected to dial switching equipment, which may be regarded as consisting of two parts designated "Originating" and "Terminating." The originating portion consists of the switching paths by which a call is routed to interoffice trunks. The terminating portion consists of the switching paths by which a call terminating in this office reaches the called subscriber.

Of the calls originated by a subscriber in this office the great majority will ordinarily be short-distance calls within what may be termed his local charge area, that is, the area within which his call is counted as one message unit if he subscribes to message-rate service, or is not counted if he pays for flat-rate service. This area may consist simply of his own exchange or may include certain nearby exchanges or zones. He dials these calls directly, if the area has been fully converted to dial operation. Such calls, in the typical case, go over direct trunks to the terminating office as illustrated at the lower left of Figure 2.

On calls to the more distant exchanges, for which there is a toll charge or a charge of more than one message unit, the subscriber dials "O" and passes his call to an operator. The switchboard provided for handling this and certain other types of traffic is included in Figure 2. The operator may complete the call by one of several methods, of which two are illustrated. If the called office is one for which there is enough traffic to warrant direct trunks, the operator extends the call over a direct trunk to that office and dials the last four digits of the called number. Many of the distant offices, however, receive too little traffic from this office to warrant an individual group of direct trunks and are reached through tandem switching equipment located at

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some central point in the area.² The operator extends such a call over a trunk to the tandem office and dials the complete number, thereby causing the tandem-office switches to select a tandem-completing trunk to the called office and the switches in that office to complete the connection. Whatever the method of completion, she writes a ticket showing the information needed for charging for the call.

Subscriber Dialing of Ticketed Calls

As previously stated, it is the purpose of the automatic ticketing equipment to make it unnecessary for the subscriber to place such calls with the operator but, instead, to permit him to dial them in the same way that he now dials local calls.

Figure 3 shows in block form the arrangement of switching equipment in the originating office when automatic ticketing of the type to be described has been added. In comparison with Figure 2, the amount of originating switching equipment is increased somewhat to provide paths for the added calls completed by dialing. The switchboard correspondingly is reduced. The direct and tandem trunks carrying ticketed calls, formerly appearing at the switchboard, are made accessible to the originating switches through added equipment which performs the two functions labeled "Routing" and "Recording."

The recording function presents the more novel features and will be considered first. The problems associated with it may be brought out by considering the form of record which the equipment is to produce.

Form of Ticket

Figure 4 shows a mechanically prepared ticket and a ticket of the type now written by the operator. On the operator's ticket the entry below the date is the calling party's number, ARdmore 8-2345, given by the subscriber at the time he places his call. Below are the called number and the times of end and start of the conversation period. The operator recognizes the answer of the called subscriber and the disconnect of both subscribers by observing the supervisory lamps of the cord circuit used for completing the connection and reads the corresponding times from a clock at her position whose dials show the hour, minute, and tenth of minute. The ticket provides space for entering later the conversation time, obtained by subtraction.

The automatically prepared ticket con-

tains essentially the same information, shown, however, entirely as numerals in order to permit using a simple type of printing mechanism. The first entry is the calling number, the two letters of the office name being shown in terms of their numerical equivalents as they appear on the dial. The following group of seven digits shows to the tenth of an hour the time at which the call was made. Next is a group of three digits provided as an aid to maintenance; it shows which of certain units of common equipment were involved in the handling of the call. The called number is shown similarly to the calling number.

The following two digits, though printed together for space reasons, are

plies to calls which do not extend beyond the initial five- or three-minute interval; on the relatively small percentage of overtime calls the overtime charge is subsequently added as an accounting procedure. The information up to this point is printed on the ticket immediately after the subscriber dials his call. When the called subscriber answers, timing is started under control of a synchronous timer. When the subscribers hang up, the elapsed whole and fractional minutes are printed as minutes of conversation time. The time is normally shown as a two-digit number, but provision is made for printing additional digits for the rare calls that exceed 99 minutes.

On a call which is not completed be-

Figure 2. Typical trunking methods

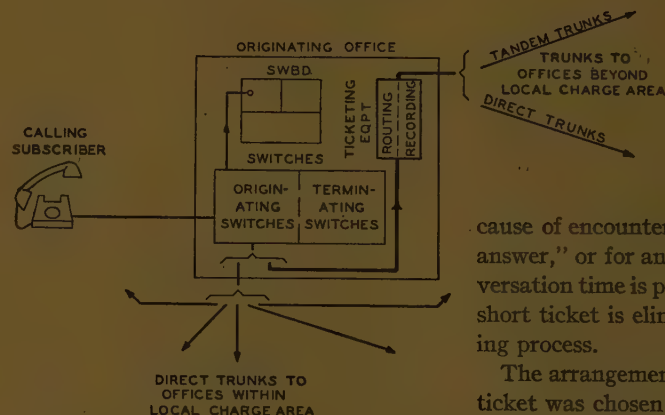
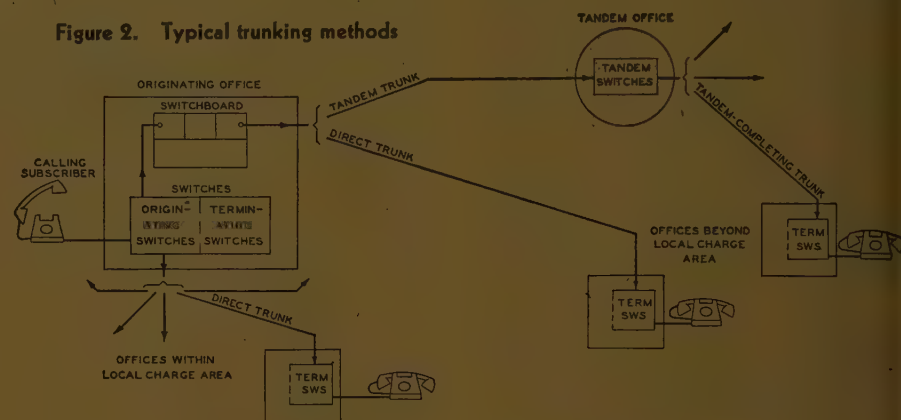


Figure 3. Trunking with automatic ticketing

cause of encountering a "busy" or "don't answer," or for any other reason, no conversation time is printed and the resultant short ticket is eliminated in the accounting process.

The arrangement of information on the ticket was chosen with regard to convenience of accounting procedures and minimizing of holding time of the various circuits involved in providing the information. Its size is that of the standard toll ticket written at long-distance switchboards and was chosen for convenience in handling and filing as well as to provide space for use with future mechanical accounting processes referred to later.

Message Ticketer

Figure 5 shows photographs of the machine, designated a "message ticketer," which prints and cuts the ticket. Power for rotating the type wheel is supplied by a small a-c motor through a friction clutch. An electromagnet controlled through a

independent. The first is the "class of service" of the calling subscriber. In some offices optional rates are offered to meet the needs of different types of subscribers, and the arbitrary digit showing this class is convenient for accounting purposes.

The following digit labeled "message units for initial interval" is the significant entry with regard to the charge for the call. The digit 3, for example, may represent a toll charge of 15 cents, or the addition of three message units to the subscriber's message usage. The equipment determines this figure from the destination of the call and the rate schedule of the calling subscriber. The figure ap-

commutator stops the type wheel, presses the paper against the character to be printed, and on its release steps the paper forward. A second magnet operates the knife. Mechanical simplicity is obtained by vesting control in external circuits connected to the ticketer when required through some 20 connecting leads. The printing speed averages about seven characters per second.

Functional Arrangement of Ticketing Equipment

The relationship of the major circuits of the ticketing system, one of which includes the message ticketer, is shown by the functional diagram, Figure 6. Each line of this diagram represents the total conductors comprising a connecting path; the path through the selectors normally consists of three conductors (the two wires of the talking circuit and a control wire), but other paths may consist of as many as 100 or more conductors. The symbols above the broken line represent, in very condensed form, the existing switching equipment of an office, while those below represent the major components of the equipment added for automatic ticketing.

The selectors shown above the broken line form part of the originating equipment of Figure 3. They consist of first, second, and third selectors which respond to the initial two or three digits of the called subscriber's number; these digits, which identify the office being called, are termed the office code. Each office corresponds to a level of these selectors. The levels corresponding to offices within the local charge area are shown connected to direct trunks leading to the respective offices. The levels corresponding to offices for which calls are to be ticketed are connected to ticketing trunk circuits and thence to the direct or tandem trunks over which the calls are to be completed.

Each trunk circuit consists of a group of relays and other telephone apparatus together with a message ticketer.

Associated with the trunk circuits there is provided a common group of senders whose functions will be described later. A sender is associated with a trunk circuit during the setting up of the call by way of an eight-wire step-by-step switch used as a trunk finder. Each sender consists of some 200 relays and other telephone apparatus used for controlling switching and recording operations.

The senders in turn have access to two or three "identifiers" which are the heart of the ticketing system. The identifier has the function of ascertaining the calling

number and other equally important functions having to do with the routing of the call. It consists of 400 to 500 relays, a number of vacuum-tube circuits, and various other apparatus.

For ascertaining the calling number the identifier requires access to terminals corresponding to the numbers of all subscribers whose lines terminate in the building and who have access to the ticketing equipment. These terminals appear on the "thousand-number" circuits, of which there is one for each thousand consecutive numbers in the building.

Other paths for interconnecting various circuits for short periods during the establishment of a call are indicated on the

functions. It provides the sender with information for routing the call, whereupon the sender sends out over the trunk the necessary pulses for setting up the call through distant switches. Concurrently, the identifier ascertains the calling number and furnishes the information to the sender. The sender, as an overlap with setting up the call, causes the message ticketer in the trunk circuit to print the initial information on the ticket. The identifier and sender are released when their respective functions have been performed.

When the called subscriber answers, apparatus in the trunk circuit starts timing. Finally, when the subscribers

Figure 4. Tickets

OPR	124	
DATE	DEC. 7 1943	
AR	8	2345
AS		
TO	At 2	
4321		
DISCONNECT	2 15 6	9
CONNECT	2 13 1	2
ELAPSED TIME		
ATTEMPTS		
CHARGES		
ATTEMPTS		

OPERATOR'S TICKET

CALLING NUMBER	MONTH DAY AND HOUR	EQPT. USED ON THIS CALL	CALLED NUMBER	CLASS OF SERVICE MESSAGE UNITS FOR INITIAL INTERVAL MINUTES OF CONVER- SATION
278-2345-1207145-031-282-4321--23-06				

MECHANICALLY PREPARED TICKET

diagram. They consist of multicontact relays which close through various numbers of wires as required for control and interchange of information between circuits.

"Day-and-hour" circuits connected to the senders control printing of the time of placing the call. Various minor circuits are omitted for simplicity.

The figures in circles show the quantities of the major circuits installed at Culver City for handling between 5,000 and 6,000 ticketed calls daily.

Method of Operation

The general operation of the system may now be traced. A subscriber making a call to a point for which a ticket is required dials the called number as listed in the directory. Dialing of the office code digits causes the call to advance through the selectors as on a local call, and to reach a level corresponding to the called office. This level, representing a destination for which calls are to be ticketed, is wired to a ticketing trunk circuit.

The trunk circuit causes a trunk finder to attach a sender, in which the further digits dialed by the subscriber are temporarily stored. The sender in turn calls in an identifier which performs two major

disconnect, the trunk circuit causes its ticketer to print the conversation time, after which it is freed for the next call.

Calling-Number Identification

Identification of the calling number presents some features of interest. As shown in Figure 6, the identifier has access, through a multicontact relay connecting path, to the trunk circuit at which the call has arrived. It has access to all the thousand-number circuits through similar paths. The principle is simple. The identifier sends into the trunk circuit a signal which finds its way back through the selectors to the terminal associated with the calling subscriber's number in one of the thousand-number circuits. While sending the signal it rapidly scans these circuits, determining successively the thousand, hundred, ten, and unit digits of the terminal on which the signal appears. These digits are transferred to the sender, which controls their printing on the ticket.

Figure 7 shows the process in more detail. The signal used is an a-c potential of about five volts at 270 cycles, impressed by the identifier on the control wire of the path through the selectors; this signal does not interfere with the normal func-

tions of this wire, nor affect the talking circuit. Connections of the control wires of the subscriber-line equipments to the thousand-number circuits are taken from terminals associated with the connector switches through which subscribers receive incoming calls and which therefore determine their respective numbers. These single-wire connections are cabled in numerical sequence to the thousand-number circuits, where each terminates in one contact of a multicontact relay and also in a capacitance-resistance network. One hundred consecutive networks may be connected in parallel to a "hundred" coil, and ten such coils are connected to a "thousand" coil. Therefore, when the a-c potential is applied to the control wire of the trunk, it follows the control

is transferred as received into the sender over a multilead connecting channel.

The foregoing describes identification within a central-office unit of 10,000 numbers. In buildings having more than one central office, the identifier first scans the central offices in succession, 10,000 or 20,000 numbers at a time, a second set of ten detectors being provided where the load warrants. The complete identification time averages less than two seconds.

The frequency of 270 cycles was chosen after a survey in working offices of extraneous potentials on control wires. The time and method of applying the detectors take account of the transients due to switching operations. Interlocks are provided to avoid conflicts when two or

segregating their lines in the switching equipment.

Class Identification

The a-c marking signal on the control wire of the switching path is used also for "class identification," which is not shown in Figure 7, in view of its similarity with the first stage of number identification. In a telephone exchange various classes of service may be offered, such as individual and party-line service with flat or message rates, or optional rate schedules differing in the extent of the local charge area. Some of these classes may require different types of equipment associated with the first selectors, or access to different paths reached by the selectors, and are accordingly segregated into appropriate line groups having access to corresponding groups of first selectors.

To enable the identifier to distinguish between classes, first selectors have networks of the type mentioned earlier associated with their control wires, and these are connected by selector groups to the proper ones of a few "class" coils. When a connection has been set up, this a-c path is therefore in parallel with that associated with the subscriber number. While the identifier is making number identification, other detectors are connected simultaneously to the class coils. The class indication thus ascertained is used for governing circuit functions and for printing the class on the ticket.

Routing Functions

As indicated in Figure 3, the second principal function of the ticketing equipment is to govern the routing of the call. This problem arises because of an inherent limitation of the simple step-by-step system with regard to the handling of calls through a comprehensive tandem system. Limited forms of tandem operation are possible through judicious choice of the numbering plan, and in fact such arrangements are extensively used in the Los Angeles network. The following, however, will indicate the nature of the problem of handling calls through a centralized tandem office such as was indicated in Figure 2.

Assume that the subscriber is calling a distant office reached through tandem and has dialed the office code digits of the number. These digits have controlled directly the various selectors and have caused the call to arrive at a selector level as indicated in Figure 6. The selector level is connected to a trunk terminating on tandem-office switches which must be supplied with the digits required



Figure 5. Message ticketer (front and rear views)

wire back through the switches to the calling line and causes a signal to appear in the output winding of the appropriate "hundred" coil and "thousand" coil.

Each identifier has ten amplifier-detectors which it can connect through the thousand-number connectors to ten "thousand" coils. Finding a signal in one of them, it registers the digit designating that thousand on a group of register relays labeled *TH*. Through relay operations it then transfers its detectors to the ten "hundred" coils of that thousand. The hundred having been found and registered on the *H* register, the identifier operates the proper multicontact relays of the thousand-number circuit to connect those 100 terminals directly into the identifier. There it first groups them by tens and finally looks at the individual terminals of the ten, registering the ten and unit digits. The record of the number

more identifiers are proceeding simultaneously. Check tests indicate irregularities due to wiring faults and provide second trials to overcome any contact irregularities.

Additional features are provided for differentiating between the two subscribers on two-party lines. These involve arrangements at the stations to produce different electrical conditions on the line, depending on which station is making the call, and a test of the line by the central-office apparatus. Facilities are not now being provided for differentiating between the stations on four-party or on rural lines, and calls from such stations will continue to go by way of the operator. Means are provided for preventing readily completion of calls through ticketing paths from these or other stations which for any reason are not to have direct dialing, without the necessity of

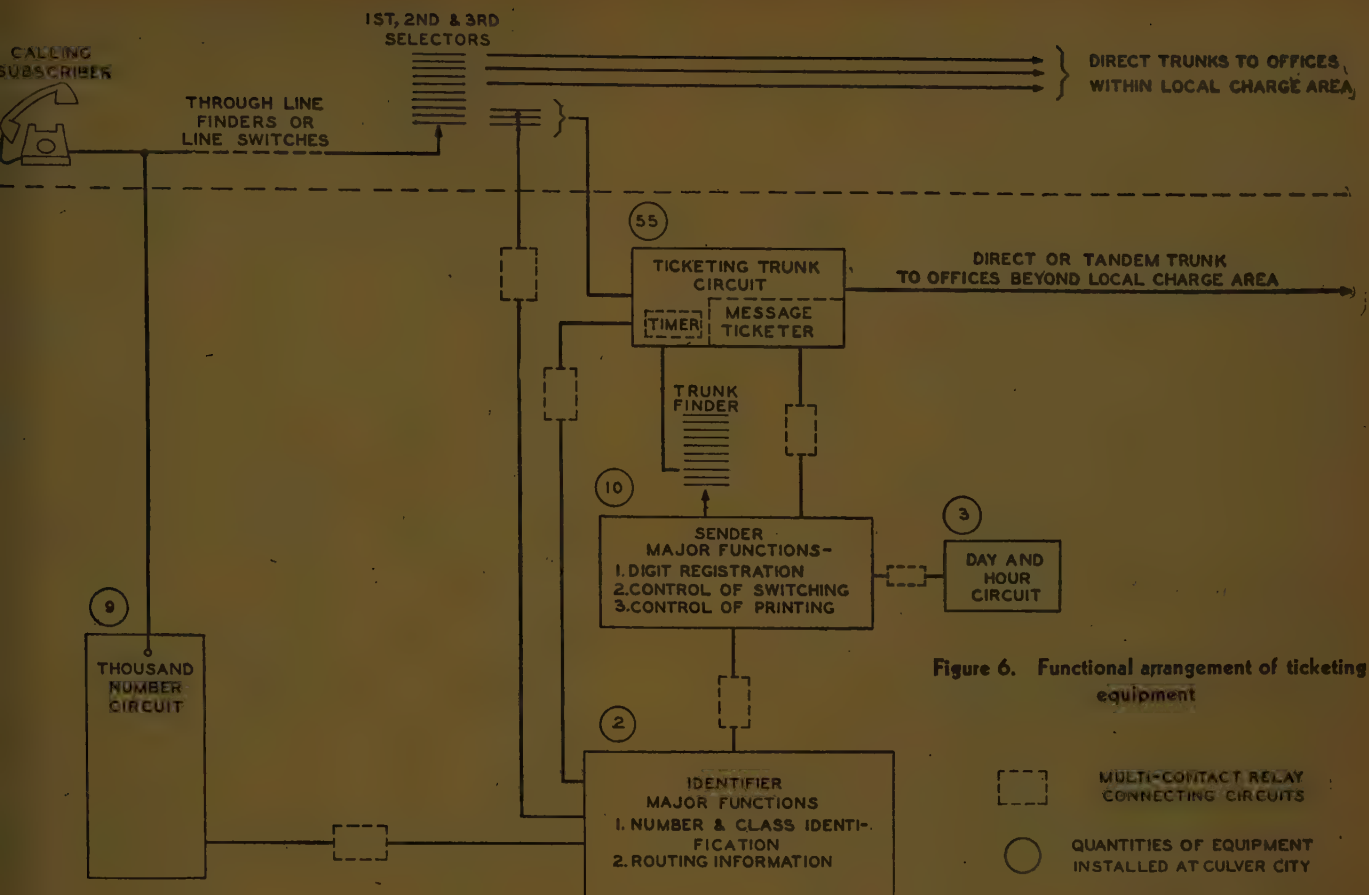


Figure 6. Functional arrangement of ticketing equipment

for directing the call to the terminating office; but these are the digits that already have been used up in the selectors of the originating office. The equipment associated with the ticketing trunks must, therefore, be capable of reconstructing these digits, meanwhile storing the addi-

tional digits being dialed by the subscriber and repeating them after the call has been extended to the terminating office.

It should be noted further that, in the originating office, the traffic to the terminating office we are considering is combined with the traffic to numerous other

terminating offices over the common group of tandem trunks and that accordingly a given ticketing trunk may be reached from a number of selector levels. The equipment, therefore, has the problem of ascertaining the selector level over which a given call has reached the trunk,

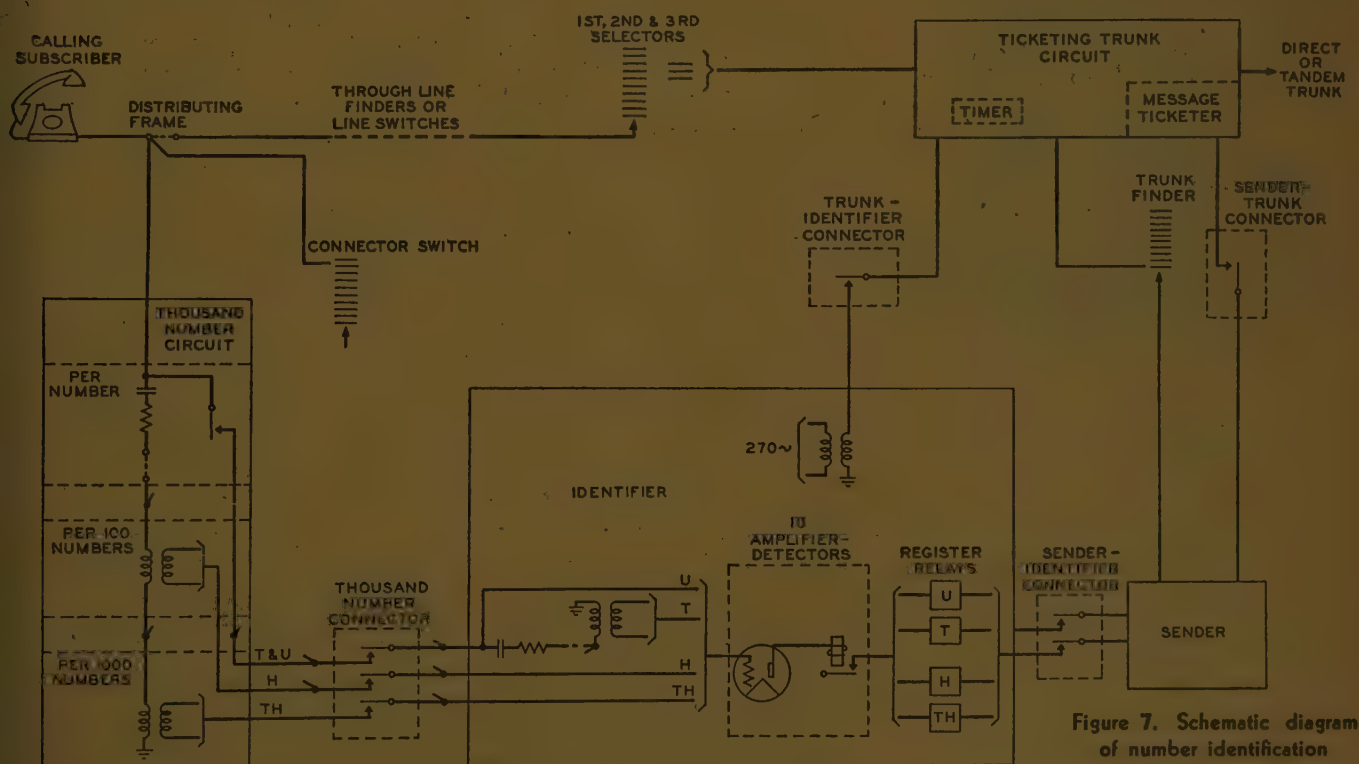


Figure 7. Schematic diagram of number identification

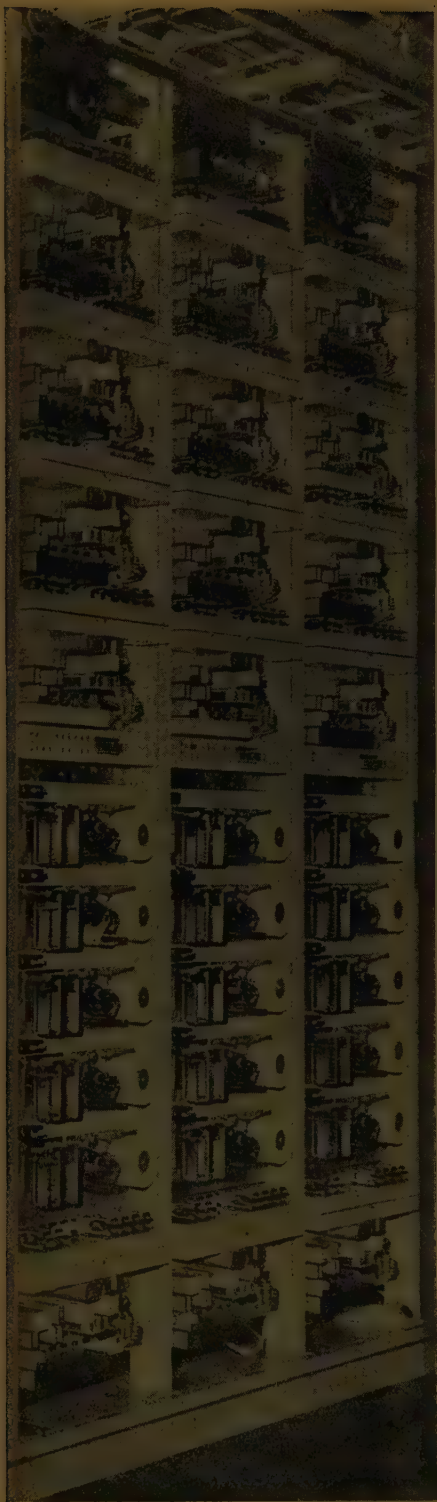


Figure 8. Ticketing trunk-circuit frames

as well as the office code digits corresponding to that selector level.

Code Reconstruction

The determination of the digits already dialed in reaching the ticketing trunk is referred to as code reconstruction. It is performed by somewhat different means than number identification, partly for reasons of speed, since it is the first step

Figure 9 (right). Sender frame (capacity three senders)



in completion of the call. Details being omitted, the identifier is equipped with a number of "route relays," which it presents to the various entrances of the ticketing trunk by way of the relay connecting circuit. A d-c signal applied to the trunk causes operation of the route relay corresponding to the entrance in use. The route relay carries contacts representing the various digits of the called office code, which can be cross-connected arbitrarily so that these digits may be given any desired numerical values. The routing information thus supplied through the route relay operates register relays in the sender. The code reconstruction process requires approximately one-half second.

Translation Features

The use of route relays in the identifier, with arbitrary cross-connections, makes it possible to provide translation; that is, to send out routing digits which may be

entirely different from the office code digits dialed by the subscriber. However, in areas for which this equipment is designed, it is generally unnecessary to provide the equipment required for full flexibility. Provision is made for direct trunking, full or partial tandem operation, and the automatic insertion of voice repeaters at the tandem office on calls requiring their use.

Automatic Alternate Routing

It will be noted that the sender receives its information as to routing of the call on the basis of the individual path over which the call has arrived from the selectors. This fact makes it possible to route calls from different terminals of the same selector level over different routes; for example, the first two or three terminals of the selector level representing a given terminating office may be connected to direct trunks to that office, whereas the succeeding terminals may be connected to

trunks to tandem. Calls which find the direct trunks busy therefore will overflow into the tandem trunks. The equipment will provide in each case the appropriate routing for reaching the same terminating office. This process is known as automatic alternate routing. It affords material economy in the design of the trunk plant because it permits provision of a small number of direct trunks used at high efficiency and combines the overflow traffic with that to other offices over the common tandem trunk group, also used at good efficiency.

Nonticketed Calls

There are cases where economy in trunk plant can be gained by taking advantage of the trunking features of the ticketing equipment and routing through it certain calls dialed by subscribers or operators for which no ticket need be printed. The equipment is arranged, under control of the class indication, to omit the ticket on such calls, and if the call is from a message-rate subscriber, to cause operation of the message register instead. Trunk circuits which omit the message ticketer entirely may be provided where economical.

Equipment Arrangements

Except for the message ticketer and an arrangement to facilitate cross-connection changes in the thousand-number circuit, the ticketing system employs no essentially new types of apparatus. The relatively complicated functions are performed by suitable interconnection of relays, small electromechanical switches, vacuum-tube circuits, and other apparatus of the types commonly employed in dial switching systems.

The frames carrying the ticketing trunk equipment are arranged to bring the five ticketers of the frame together at a convenient height as shown in Figure 8. Figures 9, 10, and 11, respectively, show photographs of sender frames, an identifier frame with the adjacent test and trouble indicator frames referred to later, and a group of thousand-number frames, as installed at Culver City.

Maintenance Features

The sender and identifier circuits are of considerably greater complexity than have heretofore been used in step-by-step switching systems. A test circuit accordingly is provided, capable of verifying numerous features for routine tests or for locating indicated trouble. In addition, there is provided a "trouble indica-

Figure 10. Trouble-indicator frame, test frame, and identifier frame



tor" patterned after that used in the cross-bar switching system. It includes a panel with numerous lamps indicating various stages of the progress of the call. It is brought into play when irregularities are detected in the operation of the ticketing circuits, and the record remains even though the second trial features may cause the call to be completed satisfactorily. The information assists the maintenance force in clearing out minor troubles before they become serious and major troubles with minimum reaction on service.

General Design Considerations

With the foregoing description of the equipment in mind, some of the general considerations entering into its design may be pointed out.

In providing direct dialing to the more distant points of a metropolitan area, consideration was given to the automatic ticketing method in comparison with another method known as zone registration.

This plan, which has been used to some extent in other dial systems, consists in operating the subscriber's message register more than once on completion of a call to a distant zone in accordance with the rate schedule, and on overtime calls to operate it further for each overtime interval. One important consideration in the Los Angeles area, however, was that the percentage of subscribers having flat-rate local service is relatively high, particularly in the suburbs, and for these subscribers it would have been necessary to add message registers used only for recording the multiunit calls. In addition, there were circuit problems in arranging the existing registers for repeated operation. Aside from technical considerations the individual record provided by the automatic ticketing method has commercial advantages which increase in importance as the distance, and consequently the charge for the call, increase.

The ticketing system has been described on the basis that a subscriber,

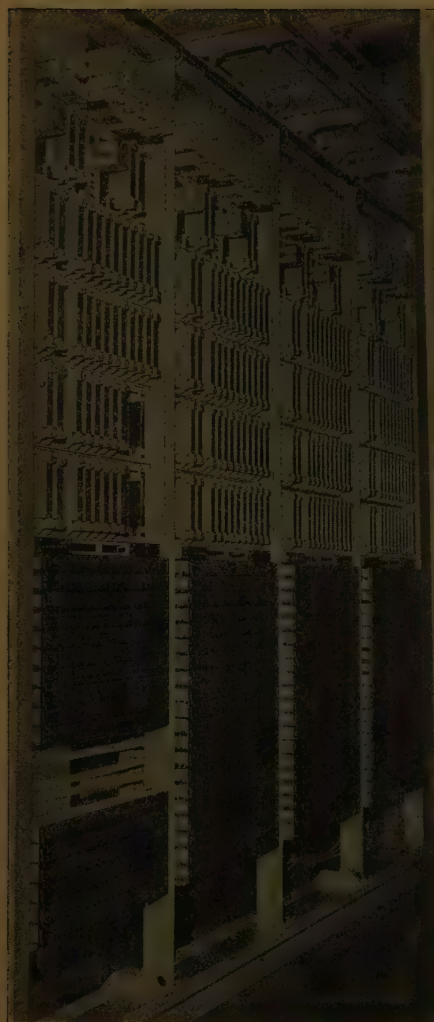


Figure 11. Thousand-number frames (capacity 2,000 numbers per frame)

calling from anywhere in the metropolitan area, will dial the number as listed in the directory to reach any other subscriber in the area. This arrangement, known as a universal numbering plan, has been adopted as the ultimate plan for exchanges included in the Los Angeles metropolitan area, now embracing some 975,000 telephones. This plan, in combination with automatic ticketing, will give the subscriber a uniform method of dialing his calls, as distinguished from the use of directing codes to be prefixed to the number on calls between different exchanges of the area.

The choice of a numbering plan for any area is, however, a telephone problem in

itself, and it only need be pointed out here that the ticketing arrangement has capabilities for being used under various plans. Its use on calls between different cities, in cases where the traffic may be sufficient to warrant, would require, in general, some form of directing codes and suitable instructions to subscribers. The ticketing plan can be adapted to such arrangements as further experience may show to be desirable.

Ease of application to existing offices was a primary factor in design. At Los Angeles all the city offices have been converted to dial operation as have also the majority of the suburbs. The ticketing equipment can be added to offices having

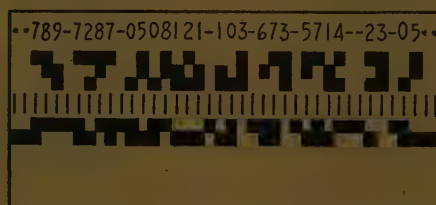


Figure 12. Ticket arranged for photoelectric scanning

either line finders or line switches with only minor modifications of a few of the existing circuits.

The technical problems of handling ticketed calls are in many ways similar to those encountered in handling traffic in large metropolitan areas in which crossbar equipment is now used.³ The techniques employed in the ticketing system have taken advantage of the developments and experience gained with the crossbar system. Some of these techniques may be pointed out.

The concentration of complicated functions in a few common circuits has various advantages but requires high-speed operation and special safeguards. High speed is obtained by the use of simple quick-acting apparatus, chiefly relays of ordinary telephone types, and the liberal use of wires for interconnection between circuits within the building. Connection is made through multicontact relays which are carefully interlocked.

Various safeguards are built into the circuits for detecting irregularities. To illustrate, registration of a digit which

may have any numerical value from zero to nine is commonly done over a group of five wires with combinations of two closures out of five. The receiving relays are arranged so that if fewer or more than two closures are received, as may occur in case of contact failure or a wiring cross, the condition is instantly recognized. Where possible, the circuit makes a second trial, using other paths if available. In any case the irregularity is registered on the trouble indicator as an aid in preventive maintenance.

Mechanical Accounting

The design of the system provides for future application of mechanical methods to the accounting processes. A possible method is to arrange the ticketer so that, in addition to the digits which it now prints, it will print also their equivalents in code marks which can be recognized by photoelectric scanning. A ticket so arranged is shown in Figure 12.

Other forms of record produced by different types of recording mechanisms may be found advantageous, and the equipment for use at the accounting center may be designed to mechanize the accounting processes to any degree found economical.

Conclusion

Further application of ticketing equipment will, of course, have to await the end of the war. In the meantime the limited installation which the Southern California Telephone Company has been able to make at Culver City will provide useful experience and a basis for further development in this phase of the telephone art.

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Fusing Practices on Distribution Systems

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DISCUSSION of fusing practices on distribution systems with numerous operating engineers gives the impression that there are almost as many practices as there are operating companies. To determine present fusing practices in this country, a questionnaire was submitted to some 200 operating companies, and replies were received from 168, indicating a real interest in this subject. The data presented here apply only to systems operating below five kilovolts and were obtained from companies located in all

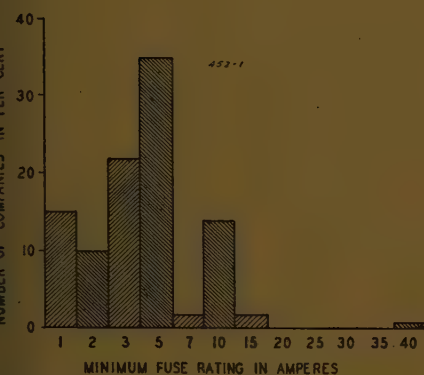


Figure 1. Minimum fuse rating employed by 167 companies

100 per cent = 167 companies

parts of the country. All fuse link data are given on the basis of N rated links. The small amount of data which was received involving 65 per cent rated links has been converted to equivalent N rating. No attempt is made to weigh the data by taking into consideration the size of the operating company, as it is the intention to show engineering thought on the subject.

Distribution-Transformer Fusing

In order better to understand the data obtained from the questionnaire, the first question asked was, "Why do you use distribution transformers?" The replies show that 80 per cent of the com-

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panies fuse to protect the system from the transformer, 59 per cent fuse to protect the transformer, 17 per cent use fuses to indicate the location of faults, and 16 per cent use them as an isolating means. While a number of companies gave only one reason for fusing trans-

Table 1. Operating Companies Using Various Combinations of Transformer and Fuse Ratings
2,400 Volts Single-Phase or 4,160 Volts Three-Phase Wye
100 Per Cent=144 Companies

Single-Phase Transformer Rating—Kva Multiply by 3 for Bank Kva)	Fuse Link Ratings—Amperes														Number of Companies in Per Cent
	1	2	3	5	7	10	15	20	25	30	40	50	65	85	
	1.5	2.1	2.2	2.8	3.3	3.5	4.0	4.6	5.0	5.5	6.0	6.5	7.0	7.5	
1	1.5	4.1	22.8	18.7	35.0	1.6	15.4	2.4							
3		2.1	44.8	33.8	2.1	13.8	3.4								
5			3.3	64.5	4.6	21.7	5.9								
7.5				0.7	9.4	25.4	53.6	8.1	1.4	1.4					
10					1.5	1.5	70.4	20.6	3.0	1.5	1.5				
15						2.6	11.8	67.1	11.2	4.0	2.6	0.7			
25							4.0	8.0	18.9	55.6	8.8	2.0	2.7		
37.5								1.4	2.8	4.2	11.2	16.1	48.9	13.3	0.7
50									1.4	0.7	4.2	6.3	23.6	54.1	3.4

formers, others gave two or more. Thus, as these percentages are based on the number of companies, the total will be more than 100 per cent.

The enclosed indicating cutout is preferred by 70 per cent of the companies for fusing the primary circuits of distribution transformers. The enclosed nonindicating cutout is preferred by 22 per cent of the companies, whereas only 8 per cent expressed a preference for the open type. The majority of operators prefer the enclosed cutout at this voltage for safety considerations. Because of the relatively close conductor spacing and pole-top congestion it is almost impossible for linesmen to avoid contact with live parts. For this reason it is common practice to insulate as much of the equipment and as many conductors as is practical. The marked preference for the indicating cutout is more difficult to explain, as in the majority of applications there is no fundamental need for the indicator. The most reliable indication of a blown fuse is the telephone of an affected customer. However, the indicating cutout has the advantage of removing the organic material from across the gap left by the blown fuse, thus eliminating trouble

caused by leakage currents across the fuse tube.

The development of repeating fused cutouts naturally raises the question as to their use in conjunction with distribution transformers. Most companies use only single-shot fuses on their distribution transformers because of their lower cost and the fact that almost all internal transformer faults are of a permanent nature. Repeating fused cutouts are used with distribution transformers to a limited extent, however, by eight per cent of the companies.

Because of the wide variations in systems and in the locations of fused cutouts it is difficult to apply them so as to keep within their published interrupting ratings. It is interesting to note that exactly 50 per cent of the companies apply cutouts at locations where the calculated

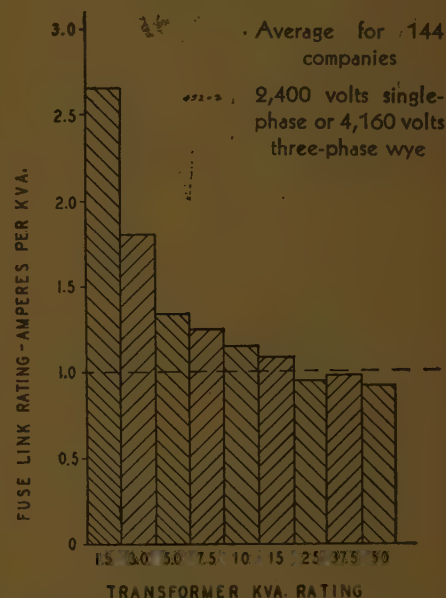


Figure 2. Weighted average of Table 1—operating companies using various combinations of transformer and fuse ratings

Table II. Operating Companies Using Various Combinations of Transformer and Fuse Ratings

2,400-Volt Three-Phase-Delta
100 Per Cent=58 Companies

Single-Phase Transformer Rating—Kva (Multiply by 3 for Bank Kva)	Fuse Link Rating—Amperes														
	3	5	7	10	15	20	25	30	40	50	65	85	100	150	200
5	1.6	21.0	11.3	61.3	4.8										
10	8.3	13.3	31.7	26.7	15.0	3.3	1.7								
15	1.5	14.7	11.8	19.1	32.4	13.2	7.3								
25		6.3	8.0	12.7	6.3	38.1	25.4	3.2							
37.5			7.1	3.6	5.4	1.8	7.1	35.7	14.3	25.0					
50					7.4	5.6	1.8	14.8	13.0	25.9	31.5				
75							8.5	8.5	10.5	59.6	12.8				
100								8.2	2.0	8.2	42.9	32.7	6.0		

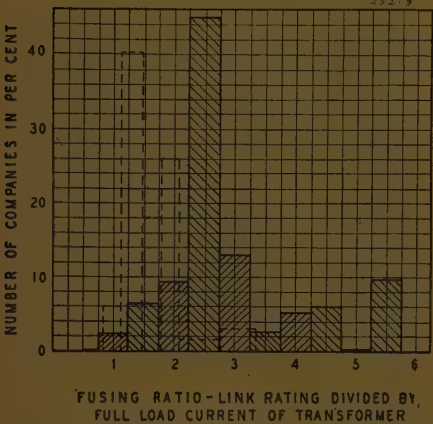


Figure 3. Weighted average fusing ratio for all ratings of transformers plotted from data of Table I

100 per cent = 144 companies

short-circuit currents are above their ratings.

Transformer Fuse Ratings

In general the major factor in determining the rating of a primary fuse for a distribution transformer is the kilovolt-ampere rating of the transformer. However, in the case of small transformers, up

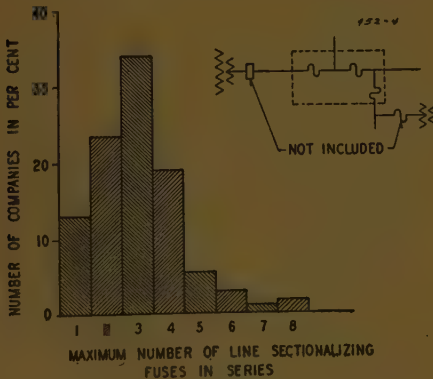


Figure 4. Line-sectionalizing practice employed by 123 companies

100 per cent = 123 companies

tions of transformer and fuse ratings. The highest percentage value is in bold-face type for each transformer rating. This table applies to 2,400-volt single-phase or 4,160-volt three-phase star systems. It is interesting to note that the old rule of "one ampere per kilovolt-ampere" is followed rather closely throughout the table except in the case of the smaller transformers. Here the rule has been dropped in favor of a higher fusing ratio because of the factors mentioned in connection with the selection of the minimum fuse rating. A weighted average of the table has been plotted in Figure 2. This figure brings out clearly the fact that the smaller transformers,

Table III. Operating Companies Using Various Combinations of Transformer and Fuse Ratings

4,800-Volt Single-Phase
100 Per Cent=22 Companies

Single-Phase Transformer Rating—Kva	Fuse Link Rating—Amperes									
	1	2	3	5	7	10	15	20	25	30
1.5	4.7	4.7	4.7	57.2	4.7	24.0				
3	9.1	9.1	50.0	4.5	22.8	4.5				
5	18.2	50.0	4.5	22.8	4.5					
7.5	4.5	45.5	41.0	4.5	4.5					
10	4.3	47.9	43.5	4.3						
15	9.1	13.6	68.3	4.5						4.5
25			24.0	57.2	9.4	4.7				
37.5				10.0	15.0	30.0	45.0			
50					5.0	20.0	50.0	10.0	15.0	

to five kilovolt-amperes or even larger, other factors usually control the fuse rating. The question was asked as to the minimum-size fuse link used on the system and the factors determining it. Lightning, transformer rating, and mechanical strength were the factors most frequently mentioned. The practice as to the minimum fuse rating employed is shown in Figure 1. The range of values is even wider than can be justified by variations in local conditions and indicates a lack of consistent practice.

Table I gives the percentage of operating companies using the various combina-

particularly the 1.5 and 3 kva, are fused much higher than the larger ones.

The weighted average fusing ratio for all ratings of transformers has been plotted from the data of Table I and is shown in Figure 3. The ratio of the minimum melting point of the fuse link to the full load current of the transformer will be twice that shown in the figure, as all these data are based on *N* rated links. Similar data gathered about ten years ago are plotted in dotted lines. Comparing the data of the present questionnaire with the previous data indicates a desirable trend toward higher fusing

Table IV. Operating Companies Using Various Combinations of Transformer and Fuse Ratings

4,800-Volt Three-Phase Delta
100 Per Cent=13 Companies

Single-Phase Transformer Rating—Kva (Multiply by 3 for Bank Kva)	Fuse Link Rating—Amperes														
	3	5	7	10	15	20	25	30	40	50	65	85	100	150	200
5	7.2	50.0	42.8												
10	28.6	57.1	14.3												
15	7.2	21.4	21.4	28.6	21.4										
25	22.2	22.2	44.5	11.1											
37.5	8.3	8.3	41.8	8.3	25.0	8.3									
50		7.7	7.7	15.4	15.4	30.7	15.4								
75			11.1	11.1	44.5	11.1	11.1								
100				6.7	13.3	20.0	33.3	20.0	6.7						

A Short-Cut Method of Estimating Telephone-Influence Factor of Power Systems With Rectifier Load

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In the planning of rectifier installations it is often desired to study the effect of the rectifier on co-ordination with communication systems. The telephone-influence factor¹ (*TIF*) is used in such studies as an index to the effect of distortion of the voltage and current-wave shapes on the inductive influence. Both voltage and current *TIF* are involved, because there are two types of induction:

Electric induction which depends upon the power-circuit voltage.

Magnetic induction which depends upon the current.

The current *TIF* is usually multiplied by the current in amperes, and the product is designated by *I·T*. In some

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distribution transformers. The old data which were given in terms of the 65 per cent rated fuse links has been converted to the present *N* rated links, and this explains the reduction in the width of the bars. One factor probably contributing to the increased fusing ratio is the change in method of rating fuse links. This automatically would increase the fusing ratio if the use of the same link ratings were continued.

Since the information contained in Table I applies to the majority of distribution systems, it has been given graphically in other forms in Figures 2 and 3 to bring out trends and factors which are not readily apparent from a table. Similar data are given in Tables II, III, and IV for other systems and are subject to the same treatment.

All companies replying use primary fused cutouts. Figure 3 shows the fusing ratios to be such, in most cases, that low-impedance secondary faults near the transformers will be cleared by the

cases of existing exposures, neither the voltage *TIF* nor the *I·T* product is significant, and the inductive effects in such exposures are negligible. In other cases one or the other or both factors are significant in connection with existing exposures, as illustrated by Table I.

The study of rectifier circuits and power-system characteristics at harmonic frequencies has made it possible to obtain fairly good estimates of voltage and current *TIF* with rectifier operation, but the usual process is rather lengthy. This involves the calculation of system impedance for at least eight harmonic frequencies,² the harmonic analysis of the rectifier current wave^{3,4} to obtain these eight or more harmonics, the weighting and summation of harmonic currents to get current *TIF*, the calculation of harmonic voltages from the values of current and of system impedance, and the weighting and summation of harmonic voltages to get the voltage *TIF*.

primary fuses. It is not surprising therefore, to find that only 12 per cent of the companies use fuses in secondary leads of some of their distribution transformers.

Line Sectionalizing

The questionnaire revealed that 85 per cent of the companies use cutouts for line sectionalizing. Of these, 54 per cent use them on the main feeders, 76 per cent on the three-phase branch feeders, and 83 per cent on single-phase laterals. The repeating cutout is most popular on the main feeders where 50 per cent are of this type, as contrasted with 41 per cent on the three-phase branches and 37.5 per cent on the single-phase laterals. About 70 per cent of the cutouts used for line sectionalizing, regardless of their location, are of the enclosed indicating type. Beyond the agreement that line sectionalizing is desirable, however, there is very little uniformity of practice. This is illustrated in Figure 4 where the maxi-

This paper describes a short-cut method of estimating the voltage and current *TIF* at the point where the rectifier is supplied, eliminating most of the steps just described by the use of curves based on average values of the factors involved. The method assumes that the supply system has an inductive reactance at harmonic frequencies, and the effect of resonance was neglected. The method does not give results that are close enough to justify its use in place of the detailed method where a thorough study is necessary, but, in most cases where it has been tried, it has given values that are near enough to test values to be representative, as will be shown later. In a complete study of an inductive co-ordination problem it may be desirable to estimate the voltage *TIF* and *I·T* product at points on the power system remote from the rectifier location, and the method described herein is not generally suitable for this purpose, except where the power system is relatively simple. In more complicated cases the use of the more detailed methods is suggested.

The method has been set up so that it can be applied to rectifiers with various numbers of phases, including 6, 12, 24, and up to 72 phases. The trend toward larger numbers of phases for the larger rectifier installations^{5,6} may be seen from Figure 1 which represents some recent rectifier installations with a combined rating of over 2,000,000 kw. This group does not include all of the large

number of line-sectionalizing fuses employed in series, between the source interrupter and the distribution-transformer fuse, varies from one to eight. In those cases where the use of seven and eight fuses in series was indicated, it is probable that the source interrupter and the transformer fuse were included. If this is true, these cases should appear in the bars for five and six fuses.

A large amount of material can be found in the technical literature dealing with this subject, and much of it is of real value. It is recognized that this is a problem to which the most satisfactory solution can be found only by combining operating experience with theoretical analysis. The data included in this paper indicate that much of the present fusing practice is based principally upon operating experience without sufficient engineering interpretation. Further study of this problem should result ultimately in better system performance with fewer ratings and simpler devices.

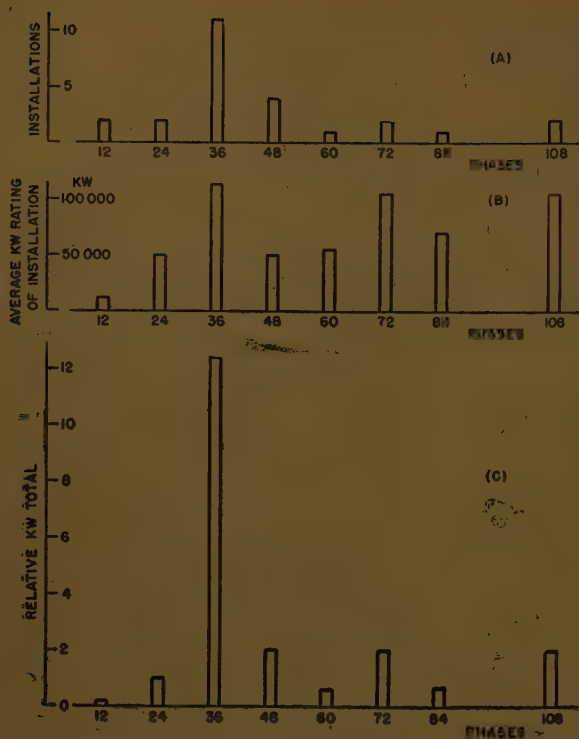


Figure 1 (left). Phase arrangements used in 26 rectifier installations, 10,000 kw and larger

- A. Number of installations using each phase arrangement
- B. Average kilowatt rating of installations for each phase arrangement
- C. Relative total kilowatts for each phase arrangement

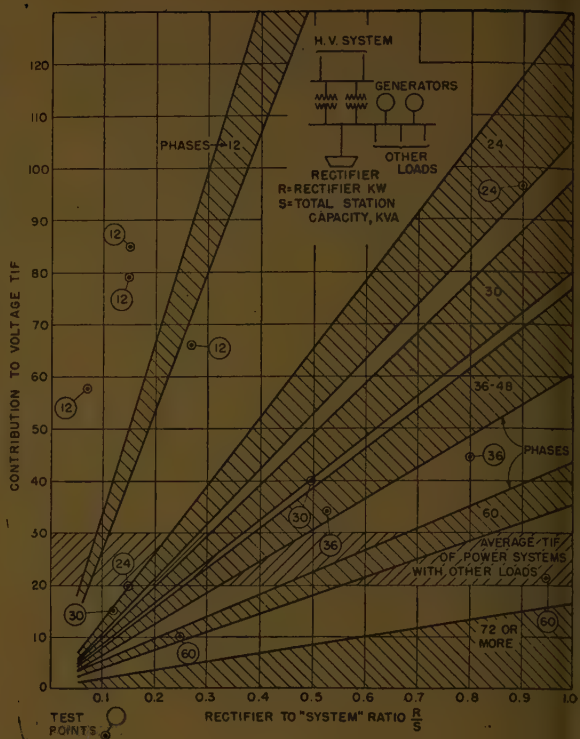


Figure 2. Curves for estimating voltage TIF, 60-cycle systems with rectifier load, 12 or more phases

Some of the test points were taken with the TIF meter in common use which is based on the 1919 weighting network (see reference 1). Figures in circles opposite test points show number of rectifier phases

installations but is believed to be representative of installations in service or under construction. Most of these installations are 36 phase, and the average installation rating for 36 phases is about 100,000 kw. It may be noted also that there are some installations with 72 or more phases.

This paper deals only with the TIF and does not consider other factors that are significant to inductive co-ordination. Some of the other factors are discussed in reports on the subject.^{2,7}

The method described here is applicable to a-c systems and not applicable to d-c systems which are supplied by rectifiers. The treatment of the d-c case by methods already in use^{3,7} is usually a fairly simple procedure.

Description of Short-Cut Method

This method of estimating voltage TIF makes use of a factor designated here as the rectifier to supply ratio R/S , because voltage TIF depends on the relative power capacities of rectifier and

source. In the case of a rectifier supplied directly from a generating station, this is the ratio of the rectifier kilowatt rating to the combined generator kilovolt-ampere rating. When this ratio is used, the TIF is read directly from a curve sheet, such as that shown in Figure 2.

The curves were calculated by assuming a supply station of a certain kilovolt-ampere and voltage, having a reactance of ten per cent referred to the fundamental frequency, on the rated kilovolt-amperes and supplying a rectifier of average characteristics. A range of rectifier kilowatt ratings was assumed, extending from one tenth of the supply-station rating up to the full station rating (ratios of R/S from 0.1 to 1.0). This includes some conditions which were used for calculations but may not apply in practice to all of the phase arrangements covered; for instance, a generating station would not be loaded with 6- or 12-phase rectifiers up to its full capacity. The rectifier current was analyzed on a percentage basis by the methods available.^{3,4} Harmonic currents in amperes

were obtained by assuming equal values of rectifier and power-station ratings ($R/S=1.0$) for the initial calculations. These currents were multiplied by the station reactance, based on the ten per cent figure, to obtain the harmonic voltages on the station bus. These harmonic voltages were weighted and combined by the root-sum-square rule to obtain the TIF which was plotted at $R/S=1.0$ on Figure 2. This TIF value would come out the same for any assumed kilovolt-amperes and voltage, because the harmonic currents and the reactance were obtained on a percentage basis. For values of the ratio R/S less than 1.0 the rectifier operates at its own full load, and the percentage harmonic currents would be the same. Starting with the same station kilovolt-amperes, the reactance would be the same, but the currents in amperes would be proportional to the ratio R/S . Hence, the TIF would be reduced in proportion to R/S and could be represented by a straight line, as in Figure 2. This neglects the effect of station reactance on the current-wave shape which is unimportant in these approximate estimates.

Calculations were made for each num

Table I. Significance of Various Influence Factors in Existing Exposures

Case	Type of Circuit		Significant Factor	
	Power	Communication	Exposure to Main Rectifier Feeder	Exposure to Branch Line
A	Cable	Either open wire or cable	Inductive effects generally negligible	
B	Overhead lines	Cable (toll)	Inductive effects generally negligible	
C	Overhead lines	Cable (local)	$I \cdot T \uparrow$	$V \cdot TIF^*$ in some cases
D	Overhead lines	Open wire	$V \cdot TIF$ and $I \cdot T$	$V \cdot TIF$

* $V \cdot TIF$ Voltage TIF.

$\uparrow I \cdot T$ Product of current times TIF.

This table is based on Table 6 of the Edison Electric Institute report.¹

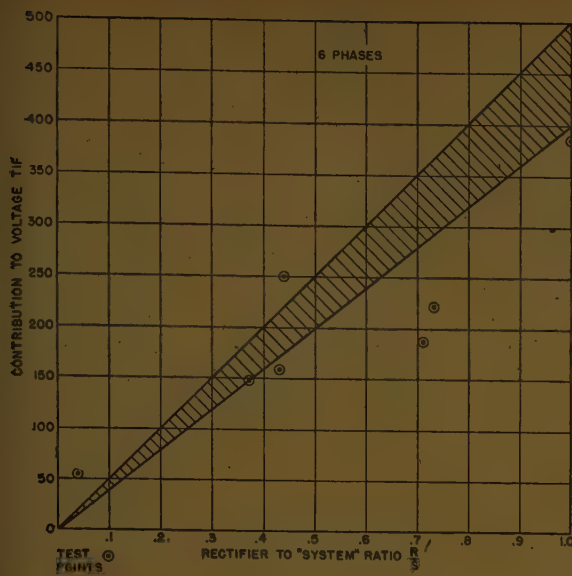
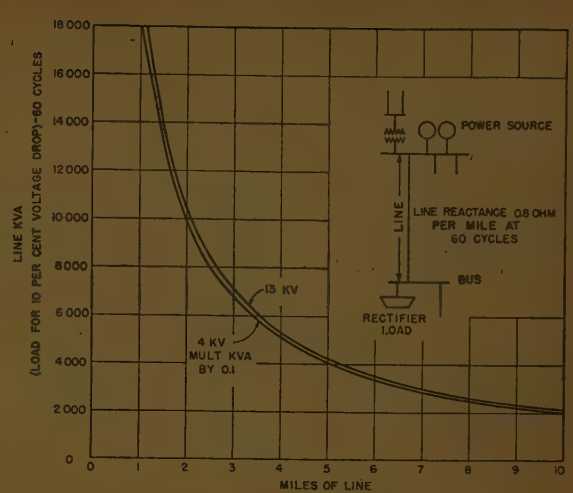


Figure 3. Curves for estimating voltage TIF, 60-cycle systems with rectifier load, six phases

The test points were taken with TIF meter in common use which is based on the 1919 weighting network (see reference 1)

Figure 4 (right). Curves for estimating linekilovolt-amperes for R/S ratio of Figures 2 and 3



ber of phases, and a curve was plotted. It may be noted that the curves of Figure 2 are drawn as zones which cover a range from about ten per cent above to ten per cent below the calculated TIF values. This implies that estimates made from the curves are not expected to be closer than ten per cent, even if the simplifying assumptions which have been made are valid in the case under consideration. If the conditions differ materially from those assumed in preparing the curves, or if resonance between elements of the supply system is an important factor, the estimates may differ from the actual results by much more than ten per cent.

Voltage TIF of 60-Cycle Systems

The curves of Figures 2 and 3 apply to 60-cycle systems and cover all of the common phase arrangements. The TIF values are based on the 1935 weighting curve.¹ Estimates of TIF are made in the following manner: When the rectifier is close to the supply station, the rectifier-to-supply ratio R/S is obtained by dividing the rectifier kilowatt rating by the total kilovolt-amperes of the station. The estimated voltage TIF at the station is read from the point on the curve sheet corresponding to R/S and the number of phases. This is the contribution of the rectifier of the total TIF. Sometimes it may be desirable to state that the estimated TIF is between the two values indicated by the zone. The procedure just described applies to rectifier load close to a generating station, a substation tied in with a larger power system, or a station which combines these two conditions, in which case the combined kilovolt-ampere rating of generators and transformers which feed into

the same bus is used. The procedure for rectifier load at some distance from the source is described in a paragraph which follows. The curves are based on ten per cent reactance referred to 60 cycles. Allowance for other per cent reactance values can be made, as illustrated in one of the examples given later (see example 1).

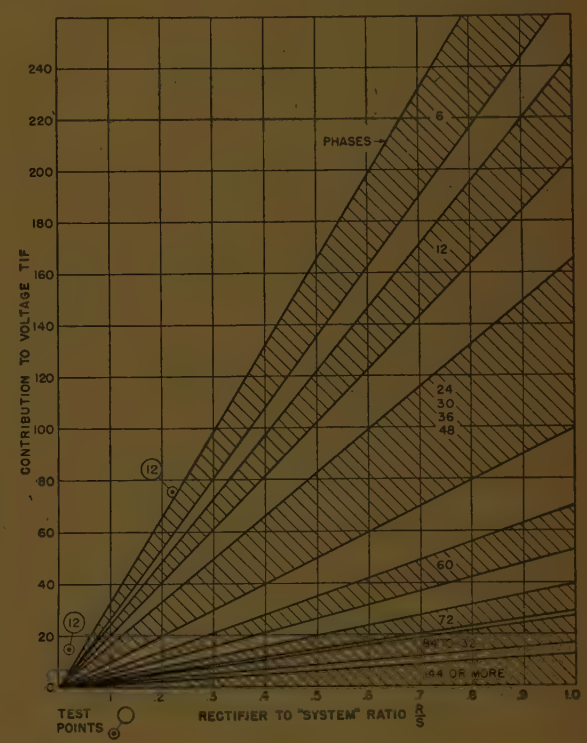
The total TIF of the station-bus voltage may be estimated by taking the square root of the sum of the squares of the rectifier contribution and the system TIF without the rectifier. If the system TIF is not known, an average value may be estimated from Figure 2.

When the rectifier is at some distance from the supply station, the line reactance may be the determining fac-

tor for the voltage TIF at the rectifier. The curves of Figures 2 and 3 may be applied to this case by using line kilovolt-ampere instead of station kilovolt-amperes. This is the kilovolt-ampere load which would produce a reactive voltage in the line equal to ten per cent of the line voltage at 60 cycles. Figure 4 gives curves for lines up to ten miles long at 4 kv and 13 kv, from which values of line kilovolt-ampere can be obtained. For other voltages the kilovolt-ampere value may be obtained by reading the kilovolt-amperes from one of the curves and multiplying by the square of the ratio of actual kilovolts to kilovolts on curve. Also, for other lengths of line the kilovolt-amperes may be read for an assumed length and multiplied by the ratio of the assumed length to the actual length. After the R/S ratio has been obtained, the curve is used

Figure 5. Curves for estimating voltage TIF, 25-cycle systems with rectifier load

The test points were taken with the TIF meter in common use which is based on the 1919 weighting network (see reference 1). Figures in circles opposite test points show number of rectifier phases



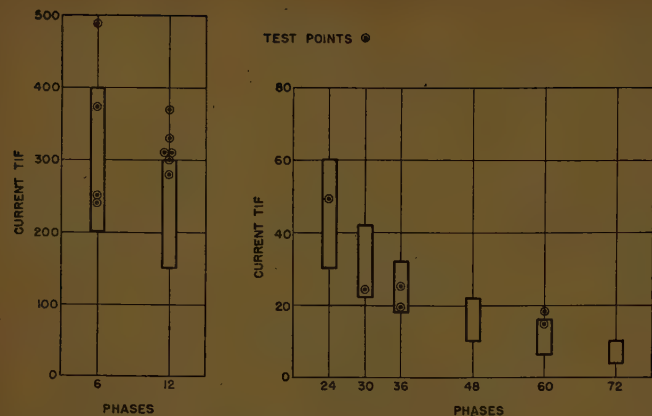


Figure 6. Chart for estimating *TIF* of rectifier input current, 60-cycle systems

Some of the test points were taken with the *TIF* meter in common use which is based on the 1919 weighting network

as already described. Sometimes both the line and the station reactances are determining factors. In such cases a value of kilovolt-amperes is determined which gives ten per cent reactive voltage in the line and station combined. This can be shown best by means of an example given later (see example 4).

The curves were calculated on the basis of inductive reactance. In power systems with cable circuits or extensive overhead lines, capacitance is a factor. In some cases resonance occurs at certain harmonic frequencies which may increase or decrease the voltage *TIF*. The method described here does not allow for resonance. The more detailed methods provide for taking resonance into account when necessary, but some approximations are involved.

Some rectifier installations have provision for adjustment of the output voltage by means of phase control (or grid control). If the range of adjustment is small, *TIF* values from the curves will be close enough in most cases. If the adjustment by phase control is over five

per cent, the voltage *TIF* may be increased in the order of 2 to 1. One of the references² gives some limited test data on this point, and another⁸ gives some calculations on effects of phase control.

The available measured values of *TIF* have been plotted on Figures 2 and 3 for comparison with the curves. Most of these values have been published.^{2,7} A majority of the 19 test points are within or reasonably close to the proper zones. The points farthest from the curve are three points for the 12-phase rectifiers where the measured values are 1.6 to 2 times the values from the curves. These tests were made on overhead systems, where resonance conditions existed, and increases of this order would be expected.

Voltage *TIF* of 25-Cycle Systems

The curves of Figure 5 apply to 25-cycle systems and correspond to those of Figures 2 and 3 for 60-cycle systems. They were calculated on the basis of ten per cent reactance referred to 25 cycles. When the voltage *TIF* is to be calculated at a rectifier which is at some distance from the supply station, values of line kilovolt-amperes may be obtained from Figure 4, which is for 60

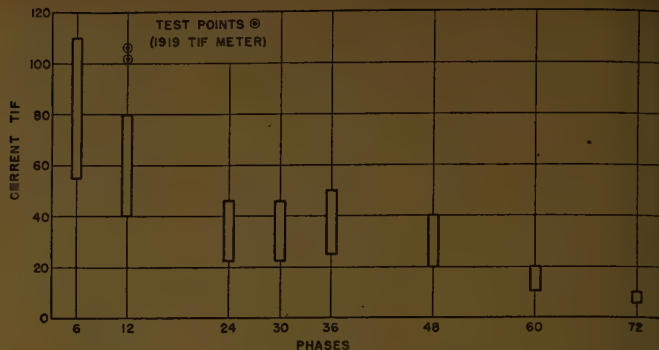


Figure 7. Chart for estimating *TIF* of rectifier input current, 25-cycle systems

The test points were taken with the *TIF* meter in common use which is based on the 1919 weighting network (see reference 1)

cycles, and multiplied by 2.4, the ratio of 60 to 25. This conversion is necessary, because reactance voltage is proportional to frequency. The available *TIF* measurements on 25-cycle systems have been plotted on Figure 5, and their agreement with the curves is comparable with the 60-cycle data.

Current *TIF* of 60-Cycle Systems

The charts in Figure 6 give approximate values of current *TIF*, based on the 1935 weighting curve, for rectifiers on 60-cycle systems. The same phase arrangements are covered, as in Figures 2 and 3, for voltage *TIF*. The shaded areas allow for the spread between different circuit conditions. The estimated *I-T* product is obtained by multiplying the rectifier current in amperes, in the a-c line supplying the rectifier, by the *TIF* from the chart. The available test data from the sources referred to under voltage *TIF* have been plotted on the charts for comparison with the calculated values. Reasonable agreement is shown in most cases. Phase control may increase the current *TIF* when the voltage adjustment is more than five per cent.^{2,8}

Current *TIF* of 25-Cycle Systems

The charts in Figure 7 give approximate values of current *TIF* for rectifiers on 25-cycle systems. They correspond

Table II. Estimates of Voltage *TIF* for the Conditions of Example 3

Rectifier (Kilowatts)	Number of 24-Phase Units	Phase Arrangement	Combination Assumed for Calculation (Values of R)	Generating Station Kilovolt-Amperes (S)	R/S	TIF Component for Each Group	TIF for Combination
40,000	2	24	24-phase R=40,000	80,000	0.5		.60
40,000	2	48	48-phase R=40,000	80,000	0.5		.35*
60,000	3	48 and 24	48-phase R=60,000	80,000	0.75		.60
60,000	3	72	24-phase R=20,000		0.25		.28
60,000	3	72	72-phase R=60,000	80,000	0.75		.13*
80,000	4	48	48-phase R=80,000	160,000	0.5		.35
80,000	4	72 and 24	72-phase R=80,000	160,000	0.5		.20*
100,000	5	72 and 24	24-phase R=20,000		0.125		.15
100,000	5	72	72-phase R=100,000	160,000	0.63		.10
100,000	5	48 and 24	24-phase R=40,000		0.25		.28
100,000	5	48	48-phase R=100,000	160,000	0.63		.45
120,000	6	48	24-phase R=20,000		0.125		.33
120,000	6	72	48-phase R=120,000	160,000	0.75		.55
120,000	6	72	72-phase R=120,000	160,000	0.75		.13*

* Arrangements for minimum *TIF*.

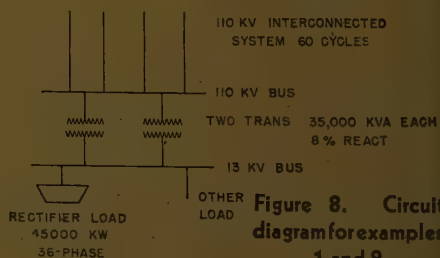


Figure 8. Circuit diagram for examples 1 and 2

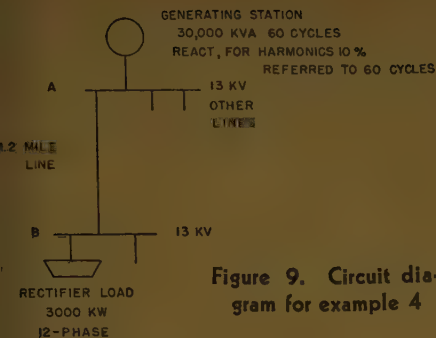


Figure 9. Circuit diagram for example 4

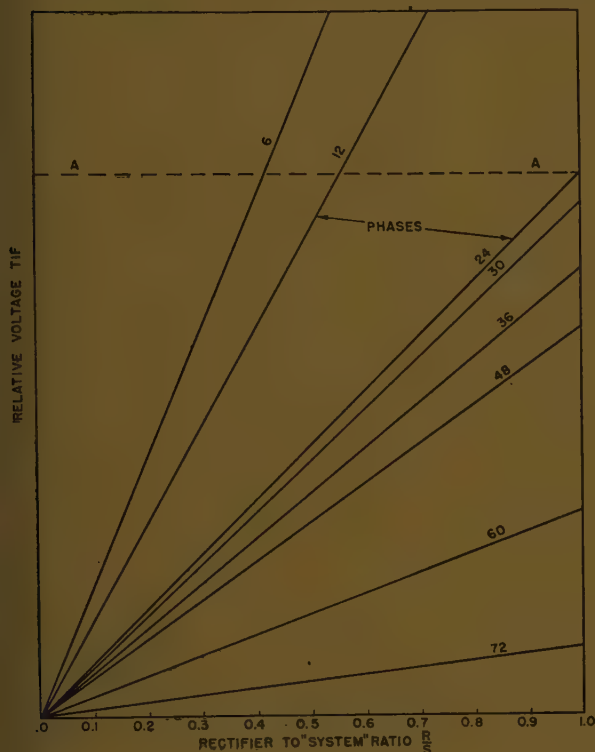


Figure 10 (left). Tentative curves for estimating voltage *TIF* with proposed weighting curve, 60-cycle systems with rectifier load. For ordinates see Figure 12

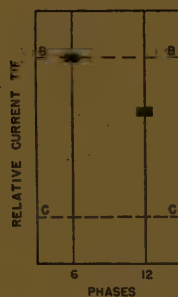


Figure 11 (right). Tentative chart for estimating current *TIF* with proposed weighting curve, 60-cycle systems with rectifier load. For ordinates see Figure 12

to those of Figure 6 for 60-cycle systems. The available test data for 25-cycle systems are indicated by test points.

Illustrative Examples

The examples which follow are given for the purpose of showing how the data in this paper might be applied to specific rectifier situations.

EXAMPLE 1

It is desired to estimate the voltage *TIF* on the 13-kv bus of the station shown in Figure 8 which supplies 45,000-kw rectifier load, 36 phase. The system *TIF* without rectifier load is 15.

The station capacity is 70,000 kva with eight per cent reactance. Since the curves are based on ten per cent reactance, we use $70,000 \times 10/8 = 87,500$ kva. Then $R/S = 45,000/87,500 = 0.52$. With reference to Figure 2, the *TIF* for 36 phases corresponding to $R/S = 0.52$ is between 32 and 40, or about 36. The over-all *TIF* at the bus is $\sqrt{36^2 + 15^2} = 39$.

In a test on a 36-phase rectifier, where the rectifier kilowatts and the station-transformer kilovolt-amperes were in the same ratio as in this example, the measured *TIF* was 34 as compared with the calculated value of 39.

EXAMPLE 2

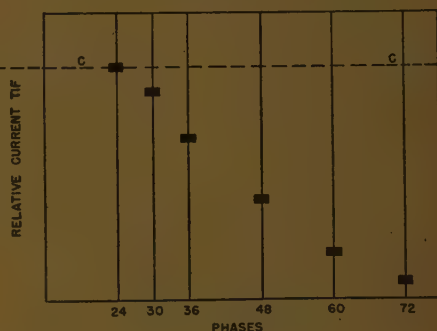
The voltage *TIF* on the 13-kv bus of example 1 is to be estimated with one sixth of the rectifier plant shut down. This is one of the six six-phase groups

If the six-phase group is removed, the *TIF* thus increases from 39 (example 1) to 56.

In the test referred to in example 1 the measured *TIF*, with one six-phase unit shut down and the other five carrying the station load, was 61. This is slightly higher than the calculated value of 56, possibly because phase control was being used to some small extent to equalize the division of load between the rectifier units.

EXAMPLE 3

In a preliminary study of a proposed rectifier installation, it is desired to estimate the effect of several combinations of rectifier units and phase arrangements.



Each unit is 20,000 kw, 24 phase. The initial installation is to be 40,000 kw (two units) supplied from a station of 80,000-kva capacity. A third unit is to be added later. Still later the generating station is to be increased to 160,000 kva and three more units added, one at a time. The frequency is 60 cycles. Since the generator reactance is not known, it is assumed to be ten per cent for harmonics.

Several combinations of 24, 48, and 72 phases might be used. Combinations, such as two units combined to give 48 phases and one additional 24-phase unit, are treated as follows. Since the 47th and 49th harmonic components are additive, a 48-phase rectifier of the full kilowatt rating (the combined rating of three units) is assumed and its *TIF* contribution taken from Figure 2. The additional contribution of the 24-phase unit is controlled mainly by the 23rd and 25th harmonics, and its value is taken from Figure 2 for the rating of the 24-phase unit. The two components are combined as the square root of the sum of the squares. The calculations and the results are shown in Table II.

The preferable combinations from the standpoint of obtaining as low *TIF* values as possible are indicated by the asterisk. These combinations are 48

of which the 36-phase installation is composed. The 36-phase connection suppresses all of the six-phase harmonics up to the 35th and 37th. The vector sum of five units is therefore equal in magnitude to one unit for these harmonics. The 35th and 37th harmonics, however, are all in phase. If it is assumed that the full load is being carried by the five units, the combination will be treated as a 36-phase rectifier of the total rating and a superimposed 6-phase rectifier of one fifth of the total capacity.

For the 36-phase component

$$\frac{R}{S} = \frac{45,000}{87,500} = 0.52$$

TIF = 36 from Figure 2

For the six-phase component

$$\frac{R}{S} = \frac{1}{5} \times \frac{45,000}{87,500} = 0.1$$

TIF = 40

Total rectifier contribution to *TIF*

$$= \sqrt{36^2 + 40^2} = 54$$

Over-all *TIF* at bus

$$= \sqrt{54^2 + 15^2} = 56$$

phase for two units (initial installation), 72 phase when the third unit is added, 72 phase and 24 phase with four and five units, and finally 72 phase for the whole installation of six units. The conversion from 48 to 72 phase when the third unit is installed could be provided for in the beginning by furnishing phase-shifting transformers with suitable taps to reduce the phase displacement.

EXAMPLE 4

With reference to Figure 9, it is desired to estimate the voltage *TIF* at the station bus *A*, the rectifier bus *B*, and the *I·T*

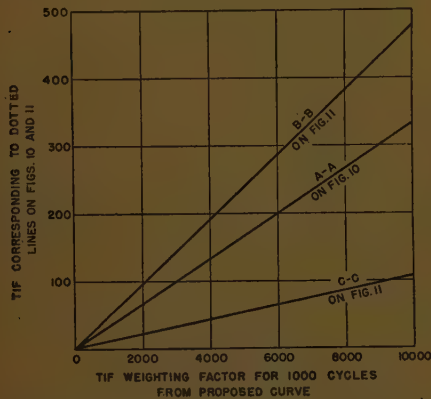


Figure 12. Scale of ordinates for Figures 10 and 11 corresponding to various proposed scales for new *TIF* weighting curve

product for the rectifier feeder *AB*. The rectifier rating is 3,000 kw, 12 phases, and the generating-station rating is 30,000 kva. The rectifier feeder is 1.2 miles long.

To estimate the *TIF* at the station bus *A*, the ratio $R/S = 3,000/30,000 = 0.1$ is used. If we refer to Figure 2, the *TIF* is about 30.

To estimate the *TIF* at point *B*, the following calculation is made:

line kilovolt-amperes = 17,500 for 1.2 mile line (from Figure 4)

station kilovolt-ampere = 30,000

total kilovolt-amperes for *S* at ten per cent is then

$$\frac{17,500 \times 30,000}{47,500} = 11,000$$

$$\frac{R}{S} = \frac{3,000}{11,000} = 0.27$$

With reference to the curve for 12-phase rectifiers in Figure 2 the *TIF* is approximately 80.

To estimate the *I·T* product for the feeder, the current *TIF* is about 225, from Figure 6. The line current is

$$I = \frac{3,000}{1.73 \times 13} = 133 \text{ amperes}$$

Then

$$I \cdot T = 133 \times 225 = 30,000 \text{ approximately}$$

In a test where the ratio of rectifier kilowatts to station kilovolt-amperes and the ratio of line reactance to generating-station reactance were about the same as in this example, the measured *TIF* at the rectifier was 65. Also, the measured *I·T* referred to 13 kv, since the line voltage was different, was 42,000.

Conclusion

Herein is described a practical short-cut method of estimating power-system *TIF* at a rectifier supply point. It is based on previously demonstrated methods of calculating harmonics produced by rectifiers together with certain simplifying assumptions as to the characteristics of rectifier and power circuits. The results are reasonably consistent with test data. The method should be useful, especially where a number of conditions have to be investigated in a preliminary study, since it requires only a few minutes to make the calculations for each condition when the pertinent data are at hand. The results may be useful also for checking other calculations. The method is applicable to the arrangements of 24 or more phases that are being used for large rectifier installations as well as to the 6- and 12-phase arrangements used for the smaller stations. In a co-ordination study the *TIF* has to be considered in combination with other factors, such as the type and location of circuits. This is pointed out in the introduction.

Appendix

Recent tests on telephone equipment have resulted in a new frequency weighting curve for message circuit noise.² A proposed *TIF* weighting curve based upon these data has been agreed upon as to shape. The magnitude of the peak or other ordinate has not been decided upon yet. The next step in the program is to make studies of electric apparatus and systems with the object of

arriving at the weighting curve of this shape which will give the best correlation between data taken with new type instrument and data taken with the existing *TIF* meter. This appendix gives data to show the effect which the proposed revision would have on the calculations described in the paper.

The establishing of the shape of the curve made it possible to plot curves showing relative *TIF* for various numbers of rectifier phases. Figure 10 shows a set of curves of voltage *TIF* for 60-cycle systems with rectifier load which is similar to Figure 2 for the 1935 weighting curve, but the ordinates are not marked. However, a scale of ordinates can be drawn for any given weighting curve of the required shape in the following manner: First, the weighting factor for 1,000 cycles is read from the proposed weighting curve. Then reference is made to Figure 12 which gives the *TIF* corresponding to the dotted line *AA* on Figure 10. The *TIF* corresponding to any other ordinate can be obtained by proportion, or the ordinate scale can be graduated suitably. Figure 11 shows charts for current *TIF* similar to those of Figure 6 for the 1935 weighting curve. As in the case of voltage *TIF*, the ordinates are not marked. *TIF* values corresponding to any given weighting curve of the required shape can be obtained with the aid of Figure 12 as already described. It is believed that these curves will be helpful in studies of the proposed *TIF* with reference to rectifier installations.

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The Functions of Ground Preference in Carrier-Current Relay Schemes

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ALMOST all of the more common present-day carrier relay systems employ a feature known as ground preference which enables the ground relays, during faults involving ground current, to take preference over the phase relays in controlling the starting and stopping of the carrier signal. The specific system conditions which require this feature are not well understood, nor is it generally understood that under certain conditions ground preference can cause trouble, or that even in some cases phase preference is "preferable." It is the purpose of this paper to discuss, in general, the reasons for and conditions pertaining to the preference feature.

The most common type of carrier relay system now in general use is the intermittent carrier system employing distance-type relays to control carrier, carrier being transmitted only in the unfaulted line sections to block tripping. There are two variations of this scheme; one using a three-zone impedance relay to start and stop carrier by circuit-closing contacts, and another using a three-zone reactance relay to start carrier by a circuit-opening contact and to stop carrier by a circuit-closing contact. These two arrangements are shown in Figure 1 in only enough detail to illustrate how the preference feature is obtained. The circuit-closing arrangement is shown in Figure 1a. Closure of the phase or ground start contacts connects the cathode of the master oscillator tube to battery negative, which is the condition for oscillation; and opening of the stop contacts returns the grid to the nonoscillating condition. The phase start contact is operated by a fault-detector impedance element and the phase stop contact is operated by an element whose coil is energized by a second impedance element whose contacts are in series with the single-phase directional-element contacts. The

ground start contact is operated by an overcurrent element with a low current setting while the ground stop contact is operated by an auxiliary element energized from an overcurrent element with a high setting, whose contact is in series with the ground directional contact. It is evident from this diagram that the ground relays can start and stop carrier regardless of the position of the phase contacts. Also it is clear that a phase preference could be obtained by interchanging the position of the phase and ground start and stop contacts and that no preference is obtained by paralleling the phase and ground start contacts. Figure 1b shows the schematic connections for the reactance-relay carrier system. Carrier is started by opening any one of the voltage-restrained fault-detector contacts, thus removing the carrier control lead from battery negative which is the carrier-transmission condition. Carrier can then be stopped by the closure of the phase stop contact which is operated by a single-phase voltage-restrained directional element. Carrier is started on ground faults by the opening of the ground start contact on a low-set overcurrent relay and is stopped by the closure of a high-set overcurrent contact and a directional contact. It is clear that the ground relays have preference in controlling over the phase relays. Also, phase preference or no preference can be obtained by the proper regrouping of the contacts.

There are a number of system conditions presented to the relays during faults involving ground current which may cause failure to block through carrier unless steps are taken to prevent such action. The ground-preference feature is one of these steps. Fundamentally, the trouble results from the fact that during single-phase-to-ground faults, and especially during two-phase-to-ground faults, both the phase and ground relays respond. It is possible that, under certain conditions, the ground relays will see an external fault as such, whereas the phase relays may view the situation as an internal fault. On the other hand, under certain other conditions, the phase relays may view the situation correctly,

but the ground relays may not see the correct picture.

An example where the phase relays may see a fault as internal, whereas it is an external fault, correctly seen by the ground relays, is the case where the current fed through a line section to an external fault is mostly zero sequence. Figure 2 depicts a condition of this kind which has been made extreme for simplification. For a single-phase-to-ground fault on the line out of substation *D*, power is fed from station *B* to the grounding bank at *A*, and zero-sequence fault current is fed over all three phase wires in the line section *C-D* to the fault as is shown by the solid arrows. A power source at *E* would feed current over only one phase wire in the line from *C* to *D*.

While the conditions shown are not typical, in that a grounding bank has its power source at another point in the system, the conditions on any grounded system will approach the aforementioned conditions. That is, any transmission line between a source of power and a grounding point will carry in-phase fault currents on all three phase wires. The application of carrier relays to the line section *C-D* requires consideration of this fact. An examination of the action of single-phase directional elements reveals that under the aforementioned conditions the carrier signal at *D* is liable to be removed incorrectly by one of the phase relays. Since carrier is removed correctly at *C* by the ground relay, failure to block on the external fault results. It is evident that if star currents are used on the phase directional relays the three single-phase directional elements at *D* cannot all indicate the same direction since the currents in all three are inphase but the voltages are considerably out of phase.

As will be easily seen from Figure 3,

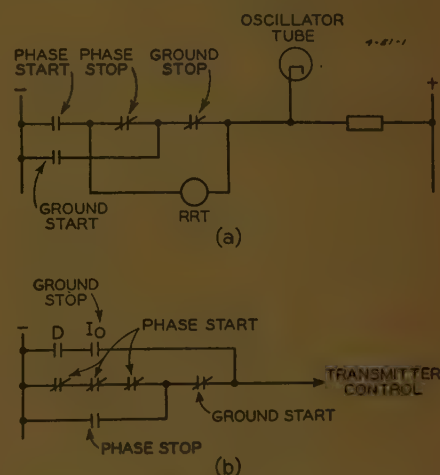


Figure 1. Schematic connections of ground-preference arrangement

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which depicts the voltages and currents applied to the relays at location *D*, directional elements with a watt characteristic and a 30 degree connection, for example, will indicate both directions. That is, the *A*-phase element using I_A current and E_{CA} voltage will open contacts for a close in external fault; also the *B*-phase element will open contacts and the *C*-phase element will close contacts.

In view of the foregoing it can be stated that any type of single-phase directional

as shown in Figure 1. There it is obvious that the incorrect indication of the phase directional elements on ground faults is of no concern since the ground relays can start and stop carrier regardless of the phase relays. The facts brought out in the foregoing yield some pertinent observations. If star currents are used in the phase directional elements the ground-preference feature definitely is needed, since the elements give false directional indications because of the flow of zero-

So far, consideration has been given only to the zero-sequence fault current from the grounding bank *A* as represented on Figure 2 by the solid arrows. On any actual power system, however, there may be a flow of positive-, negative-, and zero-sequence current from another source of power such as the transformer bank *E*. The line currents flowing from bank *E* to the fault are shown by the dotted arrows. Note that the bank *E* fault-current contribution in section *C-D* flows only in the faulted phase *A*. It is interesting to see what effect this current has in connection with the use of the ground-preference feature. When star current is being utilized, it is quite evident that the directional response of the three directional elements is not at all changed, since the additional phase-*A* current merely supplies more opening torque to the phase-*A* element and does not affect the incorrectly responding phase-*C* element.

On the other hand when the directional elements are supplied with delta current, the fault current on phase *A* from bank *E* causes the *A*-phase and *C*-phase directional elements to open contacts. This is seen from Figure 4b where I_A (representing current flow toward station *D*) with E_{CA}' and $I_C = -I_A$ with E_{BC} give opening torque. The flow of 100 per cent-power-factor load current from station *D* to *C* is represented by the star currents inside the triangle *CA'B*, and it is seen that the load current on phase *C* is substantially opposite to the fault current I_C . This means that the phase-*C* directional element cannot operate in the wrong direction unless the load current

element used for the purpose of controlling carrier will cause failure to block tripping for external ground faults under one or another of the conditions met with on a grounded power system.

The preceding is discussed on the basis that star current is used on the directional element. However, a carrier system using single-phase watt-type directional elements energized from delta current gives a different answer. It is evident that the delta connection of currents (Figure 4a), wherein the *A*-phase element receives I_A-I_B , the *B*-phase element receives I_B-I_C and the *C*-phase elements receive I_C-I_A , completely cancels out the three inphase zero-sequence currents represented by the solid arrows, and the directional elements receive no fault current. However, the delta-connected directional elements will respond to load current, and, if, while the external ground fault in Figure 2 exists, load current flows from station *D* to station *C*, carrier blocking will not be accomplished since the ground directional relay at *C* removes carrier and the phase directional elements at *D* also remove carrier.

As far as the aforementioned directional elements are concerned, the incorrect action in removing carrier on external ground faults can be eliminated by the use of a ground-preference connection such

sequence fault currents. Furthermore, the incorrect indication of the directional relay on zero-sequence fault current is augmented by the flow of load current in the opposite direction. In other words, load current flowing from station *D* to *C* on phase *C* adds more or less inphase to the zero-sequence fault current from station *C*.

Phase directional relays using delta currents require the ground-preference feature only because of the possible flow of load current opposite to the zero-sequence fault current.

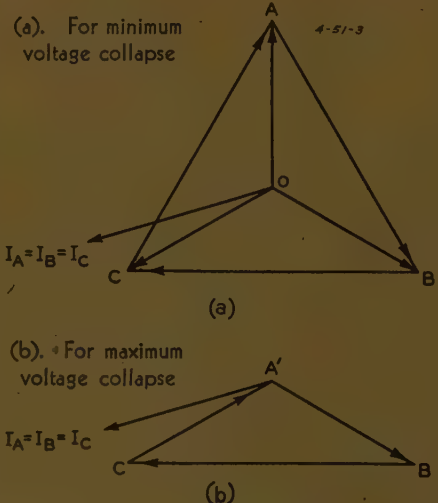


Figure 3. Current and voltage relations at station D

Figure 2. Flow of fault current on a grounded system

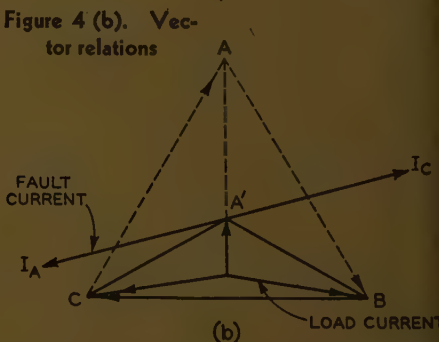
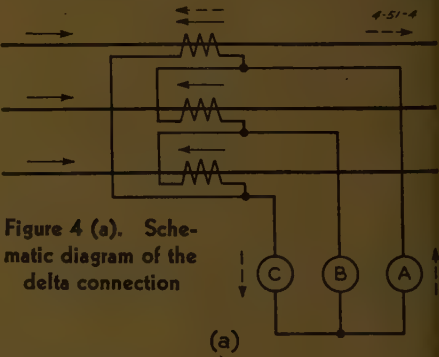
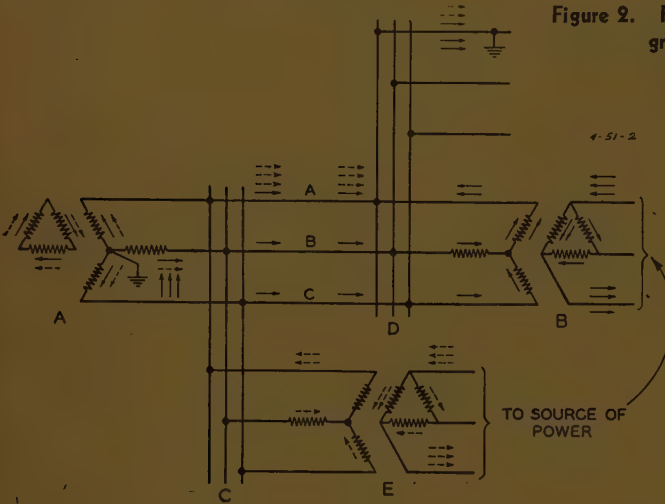


Figure 4 (a). Schematic diagram of the delta connection

Figure 4 (b). Vector relations

predominates over the phase-A fault current which is supplied by the bank E. However, fault current does not appear in the phase-B relay, and, therefore, its directional element may close contacts because of load current.

Heretofore, only the directional element has been discussed. However, present day distance-relay carrier systems employ a distance-measuring element to supervise the directional element. In one system a separate impedance element Z2 has its contacts in series with the directional element to stop carrier and complete the trip circuit through the receiver relay contacts. Another system uses voltage restraint on the directional element to accomplish the same purpose effectively.

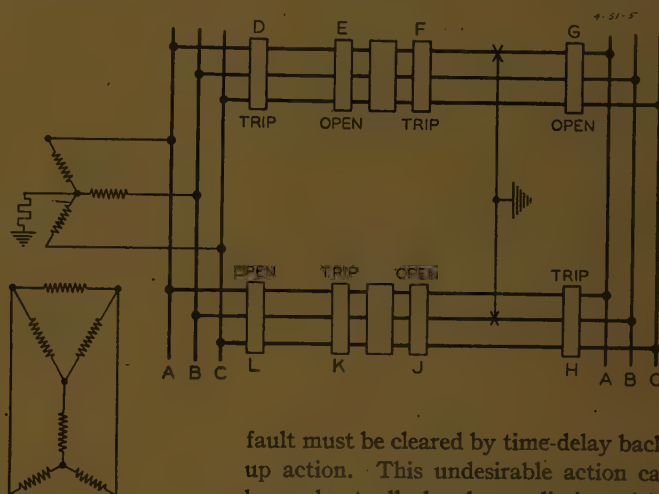
It is now necessary to see how the use of the supervising distance element affects the requirement for ground preference. In the case where the directional elements receive delta current are considered first, the impedance elements would also receive this same current, and the effect of the impedance element is as follows: If all of the fault current from C to D is zero-sequence current, the relay at D is subject only to load current, and it can stop incorrectly carrier transmission for load current flowing from D to C only if this load current is high enough to reach the pickup point of the impedance element at the voltage existing during the fault. For an external ground fault on phase A, for instance, the voltage on A-phase and C-phase impedance elements may be anything between the limits of normal for a distant fault to 58 per cent of normal for a close-in fault. In order to close the phase-B relay contacts the load current would have to operate against full normal voltage. Ordinarily, the setting of the supervisory impedance element would be considerably above the maximum load current.

When the additional fault current flowing on phase A only is considered, the conditions for incorrect operation of the relays at station D became even more difficult to attain. As was seen previously, the fault current on phase A causes the C-phase relay to act correctly and counteracts the effect of the load current. The only condition where phase-C relay could indicate the wrong direction would be for the load current from D to C to be larger than the fault current on phase A. A slightly predominant load current could reverse the phase-C directional contacts, but in order to operate the supervising impedance element the predominance would have to be con-

siderably greater than this to reach the pickup of the impedance element whose voltage is greater than 58 per cent of normal. The action of the phase-B relay must also be considered even though, as is seen from Figure 4a, it receives no fault current. However, there is load current in phase -B relay, but to get incorrect action out of this relay, the load from D to C must reach the pickup of the impedance element which has full normal voltage, and, of course, this is impossible.

In the case where star current is used, the addition of the distance-measuring element to supervise the directional element does not lessen materially the chances for incorrect operation. As was shown previously, the zero-sequence fault current on phase C may be of sufficient magnitude to operate the distance element since the restraint voltage may be

Figure 5. Schematic diagram of system requiring phase preference



reduced to 58 per cent of normal. Furthermore, this element may also be subject to zero-sequence fault current plus load current, and under these conditions it is quite possible that the phase-C relay will try to remove carrier.

The fault current from bank E, Figure 2, which flows only on phase A would, of course, have no effect on the phase-C relay.

The preceding considerations lead to these conclusions:

1. If the phase directional and distance supervising elements use star current, then ground preference definitely is needed to prevent incorrect removal of carrier on single-phase-to-ground faults because of the flow of zero-sequence fault current on the unfaulted phases and also because this current adds to the load current flowing in the opposite direction.
2. If delta current is used, then ground preference is required only if the through-fault current is all zero-sequence current and the load current in the opposite direc-

tion is large enough to reach the pickup value of the supervising impedance element at 58 per cent of normal voltage. Such a set of conditions is comparatively rare, and, therefore, if delta current is used, ground preference can be eliminated in order to take care of other conditions if necessary.

While, heretofore, the ground-preference arrangement has been used in most carrier installations with good results, it nevertheless has, upon occasions, been desirable to have some other form of preference. One instance where the ground-preference connection causes trouble is the case of a two-phase-to-ground fault involving a high ground resistance. Here the ground current may be between the pickup values of the ground-tripping overcurrent element and the ground carrier start overcurrent element, in which case carrier is put on by the ground relays but not taken off, thus blocking the phase relays from high-speed tripping, and the

fault must be cleared by time-delay backup action. This undesirable action can be, and actually has been, eliminated by removing the overcurrent element from the carrier stop circuit and making the removal of carrier by the ground relays dependent only upon the ground directional relay. This, of course, requires that the sensitivity of the ground directional relay be the same as that of the overcurrent carrier start relay. However, the sensitivity of the carrier stop element cannot be made too great, otherwise failure to block will result on external phase faults where system unbalances may produce enough spurious ground current to cause the sensitive ground-carrier stop element to operate.

While the ground-preference connections have been used extensively in carrier relay system, heretofore, it should be realized that there are certain system conditions which require phase-relay preference rather than ground preference. A specific instance where phase preference is required is the case of simultaneous ground faults in different line sections.

Influence of Improved Magnetic Alloys on Design Trends of Electrical Instruments

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Synopsis: Small panel-type electrical indicating instruments are recognized as an important component in radio, electronic, and power control equipment, which is so essential in all military and naval operations on land, in the air, and on the sea. Such instruments are required to be small, compact, light in weight, and reliable measuring devices; and one of the major factors in the realization of these requirements is the efficient utilization of improved magnetic materials for permanent magnets.

This paper describes properties of a new magnetic alloy and compares its characteristics with other permanent-magnet materials used in small panel electrical indicating instruments of the permanent-magnet moving-coil type. The use of a new cobalt-molybdenum-iron alloy as a permanent magnet material in an indicating instrument and its influence on design trends are discussed. The resulting improvement in overall instrument performance by the use of this new material is summarized, with particular reference given to mechanical factor of merit which is a measure of instrument reliability.

THE use of new and improved permanent-magnet alloys which have been developed during recent years

On systems grounded through an impedance it sometimes happens that a flashover to ground on one phase may immediately cause another flashover on another phase in another line section. Analysis of the action of directional ground relays under these conditions shows that the directional indication at several locations may be incorrect. The situation is depicted schematically in Figure 5, and it is seen that, for a ground fault on phase *A* in section *FG* and on phase *B* in section *JH*, one ground relay in each section except *DE* as indicated by "open" and "trip" operates incorrectly. If carrier relaying with ground preference were applied to this system, incorrect operation would result in both faulted sections. In section *FG* the phase relays at *F* would remove carrier but would be blocked by carrier from *G* which is held on by the ground relay. (Block-

probably has influenced the design trend of electrical indicating instruments more than any other one factor. For given sensitivities, instruments have been made available which are more sturdy and reliable, and instruments of higher sensitivity have been made possible by the use of the newer alloys. Relatively higher coercive force *H_c* and high residual *B_r* materials are now available that are readily machined and use a minimum of critical materials, factors which are of particular importance in high production designs for wartime applications.

Characteristics of Permanent-Magnet Alloys

The properties of 11 commercially available permanent-magnet alloys recently published¹ are shown in Table I.

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ing of carrier transmission by the fault is an exception). In section *JH* the same action would occur. If the carrier connections were changed to give preference to neither the ground relays nor the phase relays, then correct tripping would occur in the faulted sections because the phase relays would clear the faults. However, carrier blocking would not be obtained in section *LK*, since the phase relays would remove carrier at *L* and the ground relays would remove it at *K*. If preference were given to the phase relays, correct action in all sections would result, since the phase-relay directional indications are correct, and the distance elements easily can be set to respond to this type of fault.

Conclusions

1. The necessity for the ground-preference feature in carrier relay systems depends,

Until comparatively recently, the chrome and tungsten alloy steels were the principal materials used for permanent magnets in electrical indicating instruments, replacing the unalloyed carbon steels previously used. These alloys possess fair machining qualities and can be fabricated by either hot-forging or punching into various sizes and shapes, but they are inherently low in available energy and require a relatively large ratio of length of magnet to length of air gap. Magnets from these materials are frequently manufactured from preshaped rods or bars, cut to length, heated, and formed to the required shapes while hot by the use of special equipment. After cooling, subsequent grinding, drilling, and machining operations are performed, after which they are hardened and the air gap accurately ground. A typical finished magnet is shown in Figure 1A.

Soft-iron pole pieces are then used to provide the correct flux distribution and to insure permanency of the flux pattern. Figure 1B shows a typical magnet and pole-piece assembly.

Low coercive forces *H_c* in the order of 60 to 70, residual flux density *B_r* of 9,000 to 10,300 gauss, and total relative energy of 295,000 to 320,000 (*BH* maximum energy) are typical values for the magnetic characteristics of these alloys.

Some magnets which are used for small panel-type instruments are made from these materials in the form of laminations of thicknesses of approximately one sixteenth of an inch punched from sheet material to final shape in conventional dies and stacked to desired height after hard-

to a large extent, on the type of current connections used in the phase relays.

2. When star currents are used in the phase relays, the ground preference feature definitely is needed during the flow of fault current and load current.

3. If delta currents are used in the phase relays, the ground-preference feature is needed only in cases where the fault current is all zero sequence and extreme load currents are present.

4. Phase preference is required on systems subject to simultaneous grounds in different line sections, and if delta currents are used the phase-preference connection is feasible.

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1. A NEW HIGH-SPEED DISTANCE-TYPE CARRIER-PILOT RELAY SYSTEM, E. L. Harder, B. E. Lenehan, S. L. Goldsborough. AIEE TRANSACTIONS, volume 57, 1938, January section, pages 5-10.
2. SUGGESTIONS FOR AVOIDING FAULTY ACTION OF GROUND RELAYS, Roy M. Smith. *Electrical World*, May 1930, pages 1092-5.

Table I. Properties of Commercial Permanent-Magnet Alloys

Alloy	Typical Composition (Per Cent)	Coercive Force (Hc)	Residual Induction (Br)	B×H (Maxi- mum)	Mechanical Properties	Commercial Methods of Fabrication
1. Chromium magnet steel.....	3.5 Cr; 1 C; remainder, Fe	63.....	9,000.....	295,000.....	Hard and strong.....	Hot forge, punch and machine
2. Tungsten magnet steel.....	5 W; 1 C; remainder, Fe.....	70.....	10,300.....	320,000.....	Hard and strong.....	Hot forge, punch cast, machine
3. Cobalt (36 per cent) magnet steel.....	36 Co; 3.5 Cr; 1 C; remainder, Fe.....	210.....	9,000.....	930,000.....	Hard and strong.....	Hot forge, punch cast, machine
4. Cobalt-nickel-copper alloy.....	41 Co; 24 Ni; 35 Cu.....	440.....	5,300.....	993,000.....	Ductile.....	Cold-roll, machine, punch cast
5. Iron-nickel-copper alloy.....	20 Fe; 20 Ni; 60 Cu.....	450.....	5,300.....	1,070,000.....	Ductile.....	Cold-roll, machine punch
6. Comol magnet alloy.....	12 Co; 17 Mo; remainder, Fe.....	245.....	10,300.....	1,100,000.....	Hard and strong.....	Hot forge, punch machine, cast
7. Alnico IV.....	12 Al; 28 Ni; 5 Co; remainder, Fe.....	700.....	5,200.....	1,250,000.....	Hard and brittle.....	Cast, sinter, or grind
8. Alnico III.....	12 Al; 25 Ni; remainder, Fe.....	400.....	7,100.....	1,330,000.....	Hard and brittle.....	Cast, sinter, or grind
9. Alnico I.....	12 Al; 20 Ni; 5 Co; remainder, Fe.....	400.....	7,100.....	1,330,000.....	Hard and brittle.....	Cast, sinter, or grind
10. Alnico II.....	10 Al; 17 Ni; 12.5 Co; 6 Cu; remainder, Fe.....	540.....	7,200.....	1,650,000.....	Hard and brittle.....	Cast, sinter, or grind
11. Alnico V.....	8 Al; 14 Ni; 24 Co; 3 Cu; re- mainder, Fe.....	525.....	12,000.....	4,000,000.....	Hard and brittle.....	Cast, grind

ening and finishing. Warpage during heat treatment, variations in dimensions, and changes in the value and distribution of the flux are sources of difficulty in this type of magnet. A magnet of this construction is shown in Figure 1C. While this type of magnet design affords low cost, the strength is usually somewhat less than that obtained with the solid magnet construction.

With this construction soft-iron pole pieces, although not always used, are desirable to insure permanence of the flux pattern in the armature gap, since any changes in flux pattern may affect the instrument accuracy.

From a mechanical standpoint, it is usually more difficult with built-up construction to maintain accurate and permanent alignment and relationship of the various parts of the element assembly than with the solid magnet construction.

Increased sensitivities of instruments were made possible by the use of cobalt alloy steels as permanent magnets. Pierre Weiss of Zurich, Switzerland, investigated this material in 1912, and it was later reduced to practice by P. H. Brace of the United States and Honda of Japan in an alloy having about three times the coercive force H and about equal to the residual B found in the chromium and tungsten steel alloys. For the past 15 to 20 years, this material has been used in instruments, providing a means of producing higher sensitivities. It has been used in forged and cast forms and is most attractive from the stand-

point of high coercive force H of about 210 with total energy (BH maximum) of 900,000 but its inherent high cost limits its use primarily to the higher-sensitivity instruments where the chrome and tungsten steels are unsatisfactory.

The foregoing materials are all steels which require quenching in oil or water at high temperatures in order to develop properly their magnetic qualities.

Further phenomenal advances have been made in recent years in strength of permanent-magnet materials by the development of the aluminum-nickel-cobalt iron (Alnico) alloys which are of particular interest to the electrical-instrument designer because of their high values of coercive force and available energy as shown in Table I. These materials are characterized in electrical-instrument design by their relatively large cross section and short lengths of magnetic section to air-gap ratio, as has

been previously shown,² and are highly resistant to demagnetizing fields because of their high coercive force H_c . While the Alnico materials have been used widely as instrument magnets, their manufacture is restricted to only two methods, namely, sintered process, and casting and grinding. The first process is usually restricted to relatively small designs sometimes found ideal for damping magnets and the like, as shown in Figure 2, while the second process is used for the production of the majority of Alnico magnets.

Cobalt-Molybdenum-Iron Alloys As Applied to D-C Instruments

The ideal magnet from the standpoint of the instrument designer would be one having high coercive force, residual induction, and available energy, and which had good machining and fabricating qualities. While a material of this type

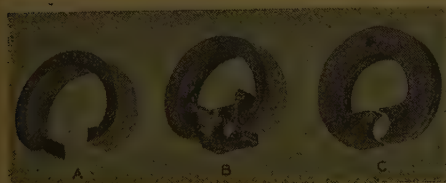


Figure 1. Forms of chrome-steel magnets

- A. Formed and machined
- B. Pole pieces added
- C. Laminated construction

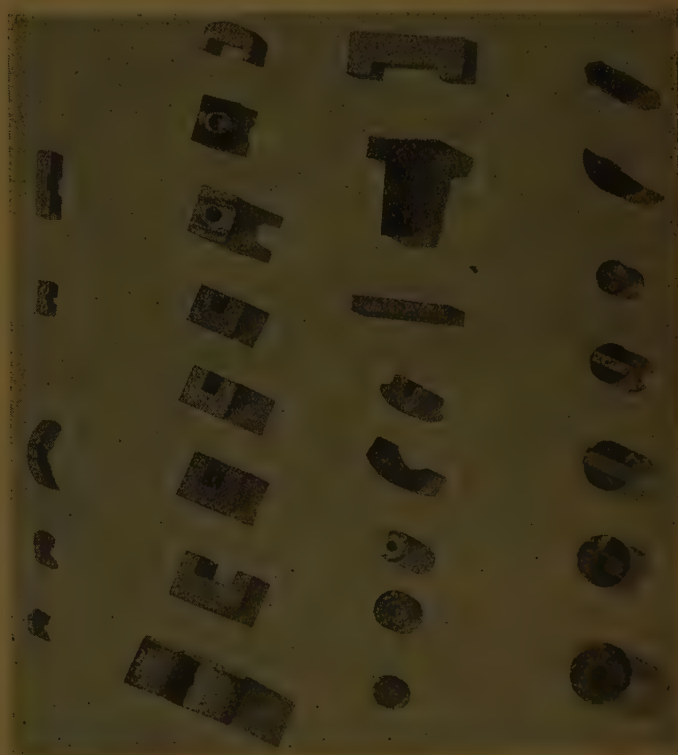


Figure 2. Sintered Alnico magnets

having magnetic characteristics equal to those of the Alnico group is not commercially available, an approach has been made in the cobalt-molybdenum-iron alloys more commonly known as Comol, as covered in Dean reissued United States patent 20800.

With the advent of Comol (typical composition: 12 per cent cobalt, 17 per cent molybdenum, remainder iron) a new material was made available which contains a minimum of the critical metals, such as cobalt, which could be cast easily and, when properly heat-treated, could be drilled, milled, and machined readily



Figure 3. Small panel indicating instrument utilizing cast Comol magnet

by conventional methods. As a result, accurate machining dimensions permit the degree of precision which is required to utilize this material fully in instrument magnets.

A coercive force H_c of about 245 is obtained as compared with 210 for 36 per cent cobalt with a residual induction B_r of 10,300, higher than either 36 per cent cobalt or Alnico II, and a maximum energy value of 1,100,000 as compared with 930,000 for 36 per cent cobalt and 1,650,000 for Alnico II.

A modification of the Comol magnet material described heretofore but con-

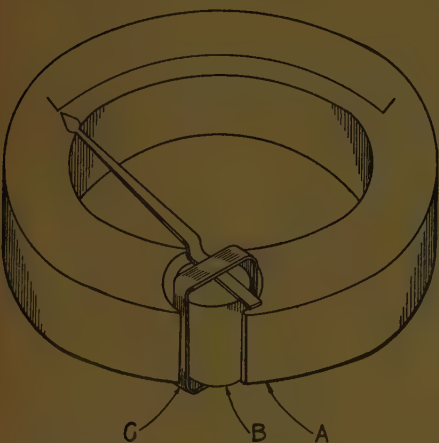


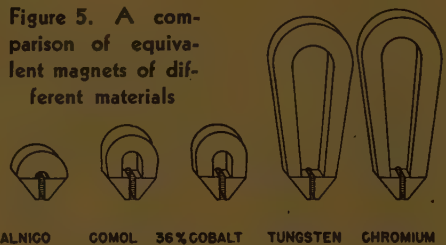
Figure 4. Basic element of permanent-magnet moving-coil instrument design

taining appreciably lower percentage of the critical elements has been utilized for the first time in instrument application as the permanent magnet in a new "thin" line of d-c and radio-frequency General Electric small panel permanent-magnet-moving-coil-type instruments as shown in Figure 3.

In view of the fact that very little information regarding the application of the newer permanent-magnet alloys as applied to indicating instruments is now available, it is proposed to treat this subject in some detail and to study the magnet circuit design as well as the moving system associated with it.

Permanent-magnet moving-coil d-c instruments of any conventional design contain certain essential parts as shown in Figure 4. *A* is the permanent magnet with suitably curved pole faces or with soft-iron pole pieces. *B* is a soft-iron cylindrical core centrally located with respect to the magnet pole faces or pole pieces so as to provide a uniform air gap

Figure 5. A comparison of equivalent magnets of different materials



in which the moving coil *C* turns upon its bearings.

The theory of operation of this type of design is well known and will be referred to only briefly at this time.

The permanent magnet *A* sets up a magnetic field in the uniform air gap, between the magnet pole faces or pole pieces and the cylindrical core *B*. The moving coil *C* is free to turn in the air gap and is equipped with two control springs, one fastened to each end of the coil, which serve to conduct the current to and from the coil and also control the pointer movement. The pointer movement is dependent upon the reaction between the

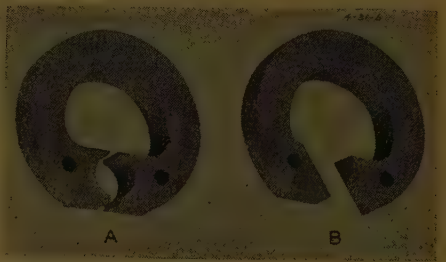


Figure 6. Forms of cast Comol magnets

- A. Uniform gap
- B. Diagonal pole face

flux due to the current in coil *C* and the flux due to the permanent magnet *A*. The turning moment or torque produced by the coil is directly proportional to the current passing through it assuming uniform flux density in the gap, and the opposing torque of the springs is proportional to the angle through which the armature turns, thus making the scale divisions upon which the value of current or voltage is measured, uniform.

From the preceding, it is seen that the permanent magnet is of utmost importance to the satisfactory operation of the instrument, and careful consideration should be given to its design.

The ideal condition in instrument magnet design from the standpoint of torque occurs when the magnetic energy maintained in the air gap is a maximum per unit volume of magnet steel. A comparison of ideal magnet sizes for a given strength of the more generally used magnet materials is shown in Figure 5. These ideal sizes are sometimes altered, however, to facilitate proper physical

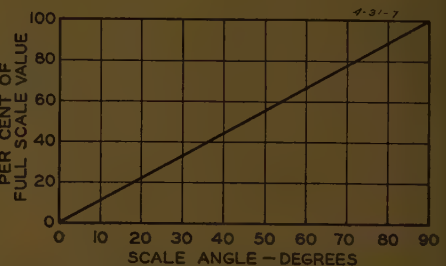


Figure 7. Typical scale distribution of indicating instrument using Comol magnet

arrangement of other instrument components.

The Manufacture of Cobalt-Molybdenum-Iron Alloy Magnets

A typical magnet of Comol material for the General Electric type *DW51* instrument previously mentioned is shown



Figure 8. Element assembly utilizing cast Comol magnet



Figure 9. A method of magnetizing the element assembly

in Figure 6A. In general the manufacture of these magnets is as follows:

The Comol alloy is compounded in a high-frequency induction furnace using relatively pure raw materials and remelt scrap. It is cast in baked sand molds to form the particular magnet desired. Following this, the magnets are given a soaking treatment at a temperature close to their melting point to destroy the "as-cast structure" and develop the necessary conditions to permit age hardening later in the process. At the end of this treatment they are quenched rapidly and at this stage are relatively soft and easily machined. The magnets are drilled, milled, or ground, as required, and then age-hardened to develop the full magnetic properties.

For the so-called linear-scale thermocouple instruments, the diagonal pole-face magnet is used as shown in Figure 6B, and the casting and machining operations on it follow those of the uniform-gap magnet shown in Figure 6A.

This material has shown very uniform magnetic potential along the pole face so as to make the use of soft-iron pole pieces unnecessary. An actual distribution provided by this type of magnet is shown on Figure 7. The lack of soft-iron pole pieces has led also to slight reductions in leakage flux as compared with similar magnets of other materials utilizing soft-iron pole pieces. In this particular design the element is assembled completely to the unmagnetized magnet in a manner as shown in Figure 8. Such a procedure is desirable from the instrument manufacturer's standpoint, since it affords an ideal method of positioning the parts correctly and reduces the hazard of the magnet picking up extraneous particles of dirt during handling.

Magnetizing the magnets after assembly not only provides greater flux density but allows the magnet to be magnetized without a "keeper" and with the soft-iron core in place, thus giving a

uniform magnetic potential along the pole face. This method eliminates the hazard of losing magnetic strength during assembly.

The ideal method of magnet saturation has been found to be by the use of a single conductor placed through the center of the magnet as shown in Figure 9 and by passing a high current through the conductor to saturate the magnet. Experience has shown that magnets of the size described herein require the following currents for approximately full saturation:

Material	Ampere Turns Per Inch
Chrome.....	500
Tungsten.....	600
36 per cent cobalt.....	1,700
Comol.....	2,000
Alnico II.....	4,400

The permanency of the magnet strength after final adjustment is important to the sustained accuracy of the instrument. While this is controllable to a large measure by the casting and aging technique, all magnets are demagnetized a few per cent in strength with an a-c field in order to stabilize them further. Changes in magnet strength with time on sample groups of magnets checked under laboratory controlled conditions have been negligible.

Changes in strength due to ambient-temperature changes on magnets made of the Comol alloy mentioned heretofore is approximately -0.017 per cent per degree centigrade rise, a value which is surprisingly close to values for ambient-temperature changes found in other magnet alloys.

Table II. Constants for Typical $2\frac{1}{2}$ -Inch-Diameter Small Panel-Type Comol and Chrome Magnet D-C Milliammeters, Accuracy ± 2 Per Cent of Full-Scale Value

	Comol	Chrome
Magnetic Circuit		
1. Total mean magnet length (centimeters).....	10.7	10.0
2. Air-gap area (square centimeters).....	0.99	1.15
3. Air-gap flux (saturated) (maxwells).....	1,980	1,495
4. Air-gap flux density (saturated) (gausses).....	2,000	1,310
5. Torque per ampere turn K (gram-millimeters) (after adjusted).....	138	0.000
Moving Element		
1. Mechanical factor of merit		
(a). For horizontal shaft (T/W).....	0.486	0.318
(b). For vertical shaft ($T/W^{1/2}$).....	0.915	0.598
2. Moment of inertia (gram-centimeter ²).....	0.52	0.65
3. Damping factor (0—full-scale minimum).....	9.4	3.6
4. Response (seconds) 0—2/3 scale.....	1.0	1.9
5. Ambient-temperature coefficient of magnet, per cent per degree centigrade.....	-0.017	-0.025
6. Maximum errors due to five gaussess		
External field		
(a). Temporary error of per cent of full scale.....	1.0	1.0
(b). Permanent error of per cent of full scale.....	Negligible	Negligible
7. Magnet stability errors due to six cycles (four hours at -40 degrees centigrade, four hours at +75 degrees centigrade, four hours at +25 degrees centigrade)		
(a). Maximum change in per cent of full scale.....	0.10	0.52
(b). Minimum change of per cent of full scale.....	0.02	0.24
(c). Average change in per cent of full scale.....	0.07	0.35

Application of Comol-Magnet Material to a New Moving System

The moving system used with this new magnet is of the internal-pivot construction with the supporting pivots mounted inside the armature shell, whereas the conventional armature has the pivots mounted outside; see Figure 10. This feature has been used in order to obtain a thin element, and the conventional type of moving system can be used equally well with this magnet.

The general objective of the moving system design is to obtain a light weight with as low a moment of inertia as is practical for required stability and overload requirements, in order to realize the best over-all dynamic characteristics and a high mechanical factor of merit.

The mechanical factor of merit has been recognized as the engineering yardstick as to the practicability of a design from the standpoint of magnitude, or pivot friction, or zero uncertainty and sturdiness, or ability to withstand abnormal usage for a long period of time. This factor may be termed as an index of the freedom-from-friction errors and is a function of control spring opposing torque for a given angle deflection divided by the weight of the moving system. It has been shown previously^{3,4} that, for the comparison of similar instruments of good commercial design having vertical shaft and V-type bearings this relation becomes:

$$\text{Mechanical factor of merit} = T/W^{1.5}$$

where

$$T = \text{spring torque in gram-millimeters for 90 degrees deflection}$$

W = weight of moving system and one control spring, in grams

For the comparison of similar instruments having horizontal shafts, this relation becomes T/W .

In good design, an effort is made to keep these factor-of-merit values relatively high which usually means high control-spring torque. The value of spring torque, other things being constant, varies as the magnet air-gap flux density as shown by the following:

The control-spring torque in the conventional permanent-magnet moving-coil design of instrument may be found from

$$T = KNI$$

where

T = total control-spring torque in gram-millimeters for 90 degrees deflection

K = magnet constant in torque per ampere turn

N = number of turns on armature

I = current in amperes in coil

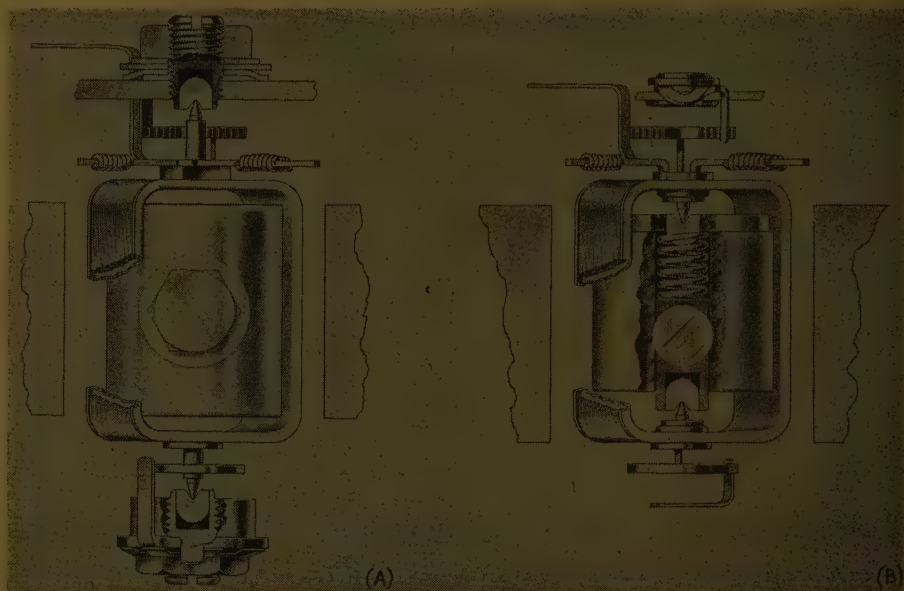
In order to keep the value of torque T as high as possible, the quantity KNI must be kept at a maximum. NI is kept as high as possible by using the maximum number of turns of wire for a given current sensitivity. Further increase in torque can be obtained only by increase in magnet strength, which makes any improvements in magnetic materials of prime importance to the instrument designer.

Consideration has to be given also to the minimum weight of the moving system. The "fixed parts" such as pointer, pivots, pivot supports, counterweight arms, and winding supports should be designed for minimum weight, but the winding will vary with sensitivity because of variation in number of turns and wire diameter used. In this particular design, the total weight of the winding will approximate twice the weight of the fixed parts for the higher-sensitivity designs and will approximate the weight of fixed parts for lower sensitivities.

A tabulation showing some of the more important constants of a typical 2 1/2-inch-diameter instrument using the high-coercive-force Comol cast magnet as compared with a conventional instrument of the same size using chrome steel formed magnet may be seen in Table II. The substantial increase in air-gap

electrical instrument has been described and its characteristics compared with other materials heretofore used for the same applications.

The application of this material has provided better over-all characteristics by virtue of increased gap flux density and has provided a basis for the design



A. Conventional instrument element design

B. New element design, General Electric type DW52

Figure 10

flux density by the use of Comol magnets provides a significant increase in the magnet constant K and the mechanical factor of merit and also improves the damping factor. With moving elements of about the same weight for the two designs and with increased magnet strength, the control-spring torque is increased, thus providing quicker response of pointer.

Conclusions

The development of a new magnet material for use in the d-c small panel

of a sturdy line of shallow electrical indicating instruments having sustained accuracy and increased range of sensitivity.

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Testing Aircraft Generators

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Synopsis: The modern fighting airplane requires a large amount of electric power for its successful operation. The aircraft generator provides a reliable source of power at the lowest possible weight. The development of these generators has required close co-ordination of design, testing, and interpretation of test results. The tests include raw material, parts, laboratory, life, mechanical, and flight tests. This paper describes tests which have been made and the interpretations which have led to improvements in d-c aircraft generators.

THE engine-mounted aircraft generator, Figure 1, operates under conditions which are more severe than in any other type of service. The generator must carry its load over an ambient temperature range of more than 125 degrees centigrade and from sea level to an altitude of 30,000 feet or more, as shown in Figure 2. Under normal operating conditions the engine vibration may subject the generator to an acceleration as great as 40 to 50 times the acceleration due to gravity. The generator also must operate successfully over a speed range as high as 2.5 to 1.

Weight must be low. Thus, each mechanical part is designed for maximum strength and minimum weight. The electric conductors are operated at current densities as high as 10,000 amperes per square inch. No excess material can be permitted in the magnetic circuit. It is essential that each part of this circuit be operated at the highest permissible flux density.

Purpose of Testing

The aircraft generator could not have been developed to its present state without close co-ordination of design, testing, and interpretation of test results. Raw materials and parts are tested and inspected to insure high quality before they are built into the machine. Each generator is given a commercial test to demon-

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strate its ability to carry the required load without mechanical or electrical failure. Laboratory tests are made to improve quality and to eliminate troubles which might develop later. Improvements are being made continuously, but these improvements must be tested thoroughly before they are adopted. An attempt is being made constantly to reduce weight, but any lightweight design must be tested first to prove that the generator is adequate, mechanically and electrically.

Quality-Control Tests

The testing of aircraft generators begins with the raw materials and parts. Insulation must be proved adequate before it is used in an aircraft generator.

Poor-quality electrical sheet steel cannot be tolerated. High loss in the laminations requires extra engine power and reduces the range of the plane. High loss also requires extra cooling air and reduces the rating of a machine of given size. Certain types of poor-quality electrical sheet steel will age in only a few hours time if operated at high flux density and temperature. This material must be avoided in aircraft generators.

The initial quality of electrical sheet steel can be determined with a fair degree of accuracy by means of the standard tests for determining losses and magnetic properties. The aging quality can be determined only by the life tests described later in this paper.

Better mechanical strength is required in the teeth of aircraft-generator-armature punchings than in the standard rotating machine. The teeth must withstand the vibration encountered on the engine in addition to the stresses imposed by the centrifugal forces produced by the high operating speed.

The mechanical strength of any ma-

terial can be determined easily by standard testing equipment. Special test equipment is required often to predict the performance in the finished generator. Some of this special test equipment is described later in this paper.

Commutators

The commutator of an aircraft generator is an especially important part. No generator can operate successfully without a commutator that is stable, both thermally and mechanically. The dimensions of the component parts must be controlled closely, and the commutator must be seasoned properly. Each commutator undergoes several cycles of heating and tightening during its manufacture, so that there will be no bar movement after it has been built into an armature.

Commutators also are given a potential test before assembly in the armature. They are tested at 1,200 volts (rms) to ground and at 110 volts (rms) between bars. These tests are made at standard

Table I. Corrosion Tests of Aircraft-Generator Parts

Salt-Spray Tests					
Part	Material	Finish	Hours Before Rusting	Duration of Test	Per Cent Surface Rusted at End of Test
Bracket.....	Steel.....	Zinc (light).....	48.....	240.....	30
Bracket.....	Steel.....	Zinc (heavy).....	.....	264.....	None
Brush band.....	Copper alloy.....	Lacquer.....	.....	240.....	No corrosion
Brush band.....	Steel.....	Zinc (medium).....	240.....	264.....	Less than 1
Brush springs.....	Steel.....	Cadmium.....	240.....	240.....	Less than 1

frequency. After the armature has been assembled it is tested at 700 volts to ground and is then given a high-frequency test to detect short-circuited coils. The armature is tested between brush positions at 750 volts and approximately 375 kilocycles (Figure 3).

Tests of Completed Machines

Each sample generator is subjected to a series of tests to determine its performance in all respects. A complete test on a sample generator consists of these items:

1. High potential, cold.
2. Neutral setting.
3. Brush run-in.
4. No-load saturation.
5. Load saturation.
6. Commutation at various loads.
7. Maximum load.
8. Overspeed.
9. High potential, hot, after overspeed.
10. Field-current check after overspeed.
11. Temperature test.
12. Losses and efficiency.
13. Ventilation.

Commutation is of great importance in d-c aircraft generators. Excessive

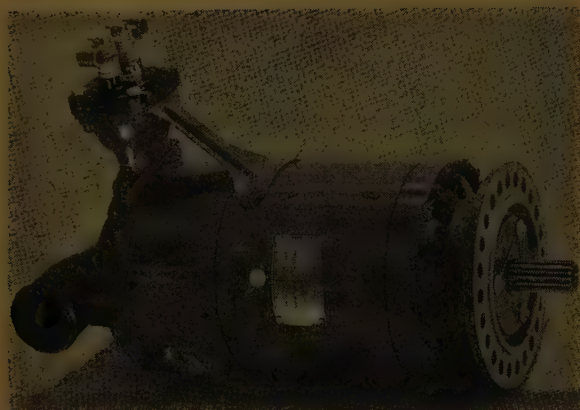


Figure 1. 28.5-volt 200-ampere type P-1 aircraft generator

sparkling causes short brush and commutator life and increased losses due to the circulating currents which are produced. Testing the preliminary sample permits the engineer to make the necessary adjustments and changes to improve commutation. The electrical performance of aircraft generators cannot be calculated nor predicted so accurately as that of large power machines. Changes after test are often necessary, but the engineer is guided by the tests in making changes. Commutation is improved frequently by a change in one or more of the following items:

1. Interpole ampere turns.
2. Interpole air gap.
3. Length of interpole.
4. Amount of compensation.
5. Neutral setting.
6. Grade of brush.

Production Tests

It is unnecessary to make complete tests on each machine that is built in daily production. Certain standard commercial tests will determine whether or not a generator will meet the expected performance. Each production generator should be given the following tests:

1. High potential, cold (500 volts rms).
2. Neutral setting.
3. Brush run-in.

4. Field current at minimum speed, maximum load, and rated voltage.
5. Overspeed test.
6. High potential, hot (500 volts rms).
7. Field-current check after overspeed test.

One production generator in approximately 20 should be given a full-load temperature test. This test should be made under standardized conditions. By comparison with previous tests any large change in losses can be detected. At regular intervals a complete test should be made, including separation of losses to provide a close check on quality of material.

Life Tests

Aircraft generators are different from standard machines, because the fullest use is made of every mechanical and electrical part. They cannot be designed for infinite life, because the weight would then become excessive. They are so designed that each part is worked to the utmost, and no part can have an excessive factor of safety. It is essential that some method be provided for determining any inherent weakness which might be present in the machine. Thus, life tests are made frequently on aircraft generators. The generator is connected to a driving motor of sufficient capacity

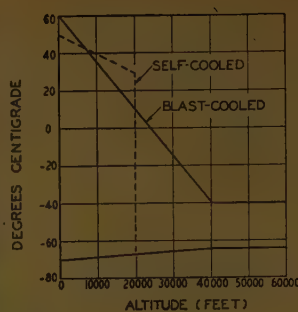


Figure 2. Temperature and altitude range of aircraft-generator operation

and then loaded at its maximum rated load. The generator may be overloaded to determine the overload capacity.

Aircraft generators may fail either for mechanical or electrical reasons. The purpose of the life test is to discover the weakest part of the generator, so that the weakness may be corrected. For best results the life test must be run over a long period of time or until some part of the machine fails.

The commutation of the generator and the brush life can be studied best by means of the life test. Since the test is continued over a long period of time, the brush life can be determined accurately, and any change in the commutation can be observed. Thus, in conjunction with altitude tests, it is possible to select experimentally the grade of brush which will give the best performance over the life of the generator. The laboratory life-test is conducted at sea level and cannot predict the performance at altitude. The brush life test must be co-ordinated with the altitude and flight tests described later.

The quality of insulation in a generator at the time of its manufacture is determined by the dielectric or high-potential test which is made during routine factory tests. These tests are no assurance that the insulation will not deteriorate and fail before the machine has operated for its expected life. The life test reproduces operating conditions and temperatures, which are found in actual service. The use of the high-potential test at frequent intervals during the life test will demonstrate any weakness in the insulation.

The losses of poor-quality electric sheet steel will increase during the life of the generator. The high operating temperature of aircraft generators has an accelerating effect upon the normal increase in losses, caused by aging. Measurement of iron loss before and after the tests will show whether or not the iron has maintained its initial qualities.



Figure 3 (left). High-frequency test apparatus for armatures of aircraft generators

Figure 4 (right). Altitude chamber for testing aircraft generators



The electrical parts of an aircraft generator are designed to withstand a higher continuous operating temperature than the bearings. If the flow of air is obstructed, so that the bearings are not adequately cooled, failure will result. The life test, continued over a long period of time, will show up any defect in bearing design, manufacture, application, or ventilation.

Insulation

Except for commutation and voltage regulation, the ability of an aircraft generator to carry load depends on the temperature of the windings. Class-A insulation will withstand a temperature of 105 degrees centigrade for a period of several years. Class-B insulation will withstand a temperature of 125 degrees centigrade for a similar period. The two classes of insulation will withstand higher temperatures for shorter periods of time. Thus, in the life of an aircraft generator, class-A insulation can be operated at 130 degrees centigrade, and class-B insulation can be operated at 150 degrees centigrade without affecting the normal life of the machine.

The temperature of the windings of an aircraft generator should not exceed that for which they are designed. High temperature can be expected in the armature, so that class-B insulation should be used where needed. The highest temperature occurs between the two coil sides in a slot. Glass-insulated wire has been found to be best for armature conductors. A thin fish-paper cell often is suitable for the slot insulation, because the temperature is several degrees cooler than it is between the conductors.

No generator can operate for its maximum useful life without an adequate factor of safety in the insulation. The insulation must withstand the temperature to which it is subjected as well as maintain the required dielectric strength. The life test is the only successful way of determining whether or not the insulation will stand up. If the generator will withstand the initial test voltage after operating for a time equal to the expected life of the generator, the insulation can be considered adequate. Similar tests resulted in the adoption of the glass-covered wire mentioned in the preceding paragraph.

Ventilation

Most aircraft generators are forced-ventilated with the air passing axially through the generator. The quantity of

Figure 5. Rotor of aircraft-generator brush tester



Figure 6. Aircraft-generator brush tester showing brushes in place



Figure 7. Curve showing contour of the rotor of brush tester

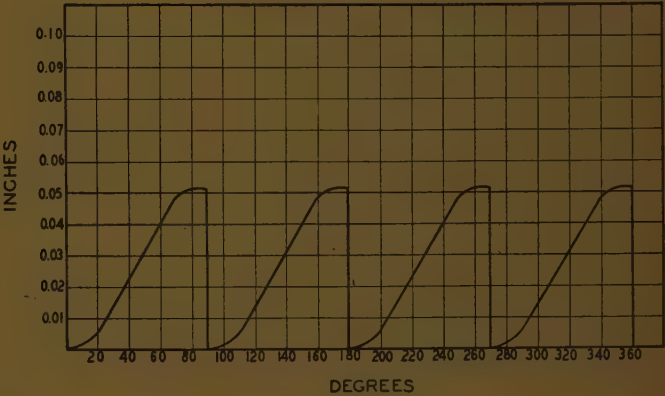


Figure 8. Fatigue-test arrangement for aircraft-generator brackets



air which passes through a 200-ampere 28.5-volt generator is approximately 75 cubic feet per minute at six inches of water, total pressure. Since the quantity is small, the air must be used effectively. All air passages should be designed so that the velocity is high. No passage should be permitted to short circuit any path where the air is needed for most effective cooling. Large openings through the rotor may prevent effective cooling of the stator.

Measurement of air pressure must be made at the generator. If measurement is made at a distance from the generator, the pressure drop between the point of measurement and the generator may be enough to affect seriously the accuracy of the test.

When an aircraft generator is installed on the engine, no avoidable obstruction should be permitted in the air passage

leading to the generator. Back pressure in the engine nacelle reduces the amount of cooling air which the generator receives. Most aircraft generators are designed to deliver their rated output when cooling air is supplied at ten inches of water, total pressure. Usually not more than six inches is available at the generator. This reduces the maximum load which the generator can carry safely.

Engine Tests

The life test gives valuable data concerning the performance of an aircraft generator but does not duplicate the actual operating conditions encountered on a plane. The engine test often is used to reproduce more closely these operating conditions. The generator is mounted directly on an engine which drives a propeller. Thus, the generator

must withstand approximately the same vibration that is encountered on an airplane.

An engine test is an excellent means of determining the ability of the generator to resist mechanical shocks and vibration. In addition, this test is a means of testing the performance of the gear unit through which the generator is driven.

Flight Test

No test has been found yet which will duplicate exactly the operating conditions that are found on an airplane. The final data as to how a generator performs must come from actual flight. These data may be obtained either from a special airplane used only for experimental purposes or from other airplanes where records are kept of flight conditions. It is difficult sometimes to obtain the complete history of the flight test.

The special test airplane has been invaluable in obtaining test data on commutation and the performance of brushes at altitude. The normal flight is one hour in ascent, three hours at altitude, and one hour in descent. The load is controlled during flight, so that operating conditions are known accurately.

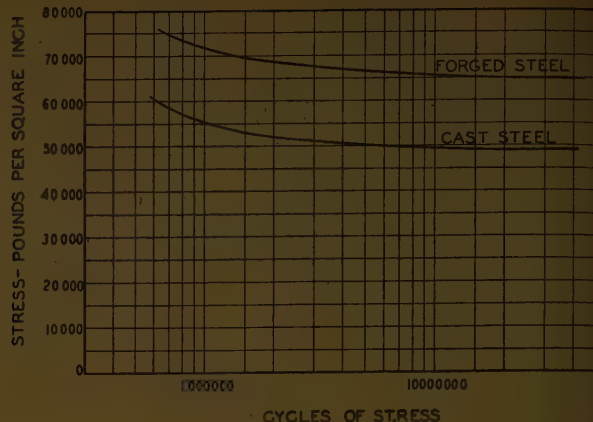
Altitude Chamber Tests

By means of the altitude chamber it has been possible to reproduce closely the conditions which are encountered when the airplane flies at an altitude of 30,000 feet or higher. A cooling system is provided, so that the low temperatures of altitude flying can be obtained. The low pressure within the chamber is maintained by means of a vacuum pump. A drive shaft extends through the wall of the chamber. Terminals are provided for electric connections. Any electrical condition which the generator encounters on an airplane can be reproduced closely in the altitude chamber. A small altitude chamber is shown in Figure 4.

Brush Tests (Mechanical)

The brushes of aircraft generators are subjected to severe mechanical operating conditions. Brushes have failed because of breakage, loose rivets, broken shunts, or frayed insulating sleeving. A vibration tester has been devised for testing brushes mechanically. The tester consists of two brush-holder assemblies mounted in a generator frame together with two commutators which have been machined, so that each brush drops approximately $\frac{3}{64}$ inch four times in one

Figure 9. Fatigue tests of aircraft-generator brackets



revolution. The tester shown in Figures 5 and 6 will test 16 brushes at one time. The contour of the rotor is shown in Figure 7. This is an extremely severe test, probably more than 100 times as severe as the condition encountered on an airplane. The vibration tester will detect any mechanical weakness in the brush in only a few hours operating time.

Brackets and Bolts

In the early days of 200-ampere aircraft generators much trouble was encountered due to broken brackets and bolts. A die-cast bracket was used on the engine end of the generator, and this was unable to withstand the vibration and shocks encountered. Trouble was encountered also with breakage of the screws which are used to attach the bracket to the generator yoke. Extensive fatigue tests were made to determine the source of trouble and how the bracket design could be improved to eliminate the trouble. The test setup is shown in Figure 8. The curves shown in Figure 9 were obtained from these tests.

Corrosion

Aircraft generators are required to operate in any kind of climate. An open piece of electrical apparatus cannot be made entirely corrosion-proof, but the parts should be made so that they will resist the weather conditions commonly encountered. To establish their ability to resist corrosion, a series of tests was made on aircraft-generator parts. These results are shown in Table I.

As a further check, outdoor corrosion tests were made on two P-1 generators completely assembled. One generator was placed under a shelter, open at the sides. The other generator was exposed completely with no protection. The generators were mounted horizontally with the air connection downward. They were taken from the assembly line and

were given no additional treatment. The generators were exposed for four weeks during the past summer. Rain fell several times during the test.

At the end of four weeks the only evidence of corrosion was a slight amount of rust on the steel parts inside the generator and on the spline. The insulation resistance varied from day to day, but at the end of the test it was as high as it was at the beginning. There was no apparent difference in the appearance of the two generators at the end of the test, although one had been under a cover, and the other had been exposed entirely. The paint was in good condition at the end of this test.

Conclusions

The test program for aircraft generators has required much testing of generator parts as well as of complete machines. The object of all of these tests has been to build the most reliable generator with the lowest possible weight. The test program has been responsible for the correction of the troubles which have developed in the field and for the elimination of potential sources of trouble. The test program is not complete and never will be complete so long as aircraft generators are built. The life test has been responsible for a great amount of improvement in aircraft generators. By means of these tests in which the generator carries a definite load, the life of insulation has been studied. It has been possible to apply the insulation, so that each electrical part is insulated adequately. Class-A material has been used where it is adequate for the operating temperatures encountered in aircraft generators. Class-B insulation has been used where required because of higher temperatures, as in the armature conductors. The insulating material has been chosen also, so that the generator will withstand the potential tests with an adequate margin.

Potential Breakdown of Small Gaps Under Simulated High-Altitude Conditions

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CONCURRENT with the present development program of a 400-cycle 208-volt power supply for aircraft, it was deemed advisable to study the effect of high altitudes on the breakdown potential between various conductors at different voltage levels.

Aircraft electrical equipment will be subjected to severe and unusual conditions which will affect materially high potential specifications. Some of the most severe conditions are:

(a). Airplanes may be parked on the ground for several weeks without seeing use. In equatorial regions the moisture content of the air may be very high and may even reach 100 per cent. Operation of equipment under such humid conditions may affect breakdown potential values.

(b). Airplanes will be flying part of the time at high altitudes (40,000 feet) and part of the time at lower altitudes. At the high altitudes all equipment not heated or lo-

cated in a heated section of the plane will get very cold. When the plane descends to lower altitudes, the humidity and temperature will be higher, and moisture will probably condense on the cold equipment, first as frost and later as moisture.

(c). In many cases airplanes are forced to fly from dusty fields or through dust storms. Any exposed surfaces may be contaminated by dust.

Scope of Investigation

The breakdown potential is that potential which causes complete breakdown or flashover between the electrodes. It is defined as the potential which will produce a luminous discharge between the electrodes. This discharge may clear itself immediately or may be followed by an arc, depending upon the power capacity and the impedance of the electric circuit. The chief characteristic of an arc discharge is the low voltage drop between the electrodes.

In order to simulate true high-altitude conditions, it is necessary to reduce both the pressure and temperature of the air which surrounds the test specimen to the same degree which exists at any specified altitude. However, several devices in

airplanes are located near pieces of equipment which operate at high temperatures and which consequently heat the air in the vicinity. These devices therefore may be surrounded by an atmosphere which is at the same pressure but at higher temperature than the air which normally exists at that altitude. It will be shown from theoretical considerations that, for any given gas pressure and electrode spacing encountered on aircraft equipment, the breakdown potential usually decreases with an increase in temperature. Since higher temperatures decrease the breakdown potentials, it was thought best to perform all tests at reduced pressures corresponding to any given altitude but to leave the air temperature fixed at its sea-level value.

In production testing of 400-cycle equipment to determine dielectric defects, a source of 400-cycle power is not usually available, and it is therefore necessary to use 60-cycle supply. A comparison between breakdown at 400 cycles and 60 cycles under similar conditions was undertaken to establish a relationship between them. This was also desirable since breakdown data which had been taken previously with 60-cycle supply could be converted to equivalent 400-cycle data.

The two types of breakdown affected by high altitudes are air-gap breakdown and surface or creepage breakdown. Designers of low-voltage electrical control equipment sometimes use air-gap breakdown values between spheres and creepage breakdown values in a uniform

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Improvements in brush life have depended mostly on generator life tests. By co-ordinating the life tests at sea level with the data obtained from the altitude chamber and flight tests, the best possible brush has been obtained. A brush has been developed which has satisfactory life both at sea level and at altitude. The subject of brush development is too broad to be more than mentioned in this paper.

The tests which have been made in the vibration tester shown in Figures 5 and 6 have enabled the mechanical development of brushes to keep ahead of the requirements in the airplane. The rarity of mechanical brush failure can be attributed to improvements which have been made as a result of tests made in the vibration tester.

The altitude chamber has not been used long enough to determine its fullest possibilities for testing generators. The

tests which have been made already show that altitude conditions can be reproduced very closely. The chamber tests in conjunction with the life test at sea level will facilitate the improvement of brushes and commutation.

The mechanical forces encountered in engine tests are nearly the same as those encountered in flight. These tests have been of great value in determining the adequacy of brackets, bearings, connectors, leads, and terminals.

The flight test permits a close check to be made on the test data obtained in the altitude chamber. Brush improvements which have been made as a result of altitude chamber tests must be given the final test in flight. Flight tests cannot be made so easily nor so often as tests in the altitude chamber but are of great value, because the generator encounters exactly the same conditions that are found in actual service. In addition to

brush tests, flight tests like engine tests have served to test the ability of brackets, bearings, leads, and connectors to stand up in service.

Laboratory tests of generator parts have enabled the engineers to improve these parts; thereby many sources of trouble have been eliminated. No untried part can be used on an aircraft generator. Laboratory tests must be relied on for a preliminary check of all improvements before they are subjected to engine or flight tests.

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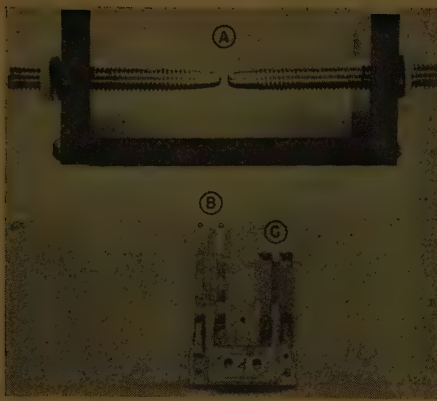


Figure 1. Air-gap breakdown specimens

- A. 1/4-inch-diameter brass hemispheres
- B. Parallel straight silver-plated phosphor-bronze strips, 0.010 inch thick. Air gap, 0.187 inch
- C. Parallel L-shaped silver-plated phosphor-bronze strips, 0.031 inch thick. Air gap, 0.117 inch

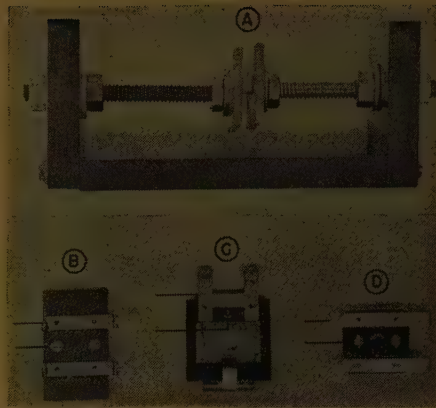


Figure 2. Creepage breakdown specimens

- A. Uniform field specimen
- B. Textolite, 0.12-inch spacing
- C. Textolite, 0.035-inch spacing
- D. Hot-molded compound, 0.13-inch spacing

alternator and transformer to limit the discharge current after breakdown occurred. A foot switch was also located in the transformer primary circuit to interrupt the circuit when breakdown occurred. In this way it was possible to use the same specimen for a large number of tests before carbonization of the specimen occurred. The breakdown potential was measured with a step-down potential transformer and a voltmeter. The wave form of the voltage across the power transformer was not a true sine wave because the alternator voltage did not have a true sinusoidal wave form. Therefore the voltages measured with the potential transformer were calibrated with voltages measured across the test specimen with a crest reading voltmeter.

The test specimens are shown for air-gap breakdown in Figure 1 and for creepage breakdown in Figure 2. All specimens, except hemispheres and the uniform-field specimens, were obtained from

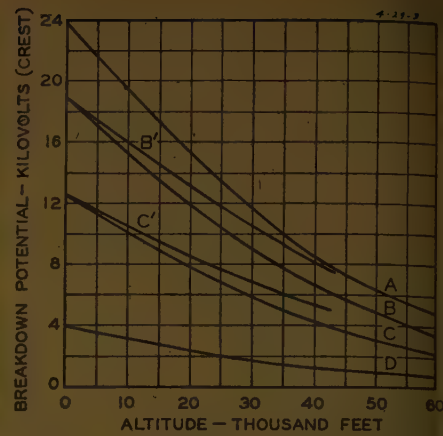


Figure 3. Hemisphere-gap breakdown characteristics

1/4-inch-diameter brass electrodes

- A. 1/2-inch gap. Air temperature 72 degrees Fahrenheit
- B. 1/4-inch gap. Air temperature 72 degrees Fahrenheit
- B'. 1/4-inch gap. Air temperature corresponds to various altitudes (calculated)
- C. 1/8-inch gap. Air temperature 72 degrees Fahrenheit
- C'. 1/8-inch gap. Air temperature corresponds to various altitudes (calculated)
- D. 1/32-inch gap. Air temperature 72 degrees Fahrenheit

standard aircraft relay parts and will simulate actual conditions which exist on aircraft.

Summary of Data

Table I shows the per cent difference between the average breakdown potential (average of ten readings) for 60 cycles with that for 400 cycles at 72 degrees Fahrenheit for reduced pressures corresponding to various altitudes. Although there are a few cases in the table in which the difference exceeds ten per cent, it should be pointed out that variations in

Test Equipment

The mechanical equipment used in performing the tests consisted of a bell jar in which the tests were conducted, a rotary vacuum pump for evacuating the bell jar, a thermometer, a humidity meter, a container of calcium chloride for drying the air, and a jar of water for raising the humidity of the air. Electrical connections to the test specimen were made through studs at the top of the bell jar.

The electric circuit consisted of a step-up transformer supplied by either a 60-cycle or a 400-cycle alternator. A series resistor was inserted between the

Table I. Comparison Between Breakdown Potentials at 60 and at 400 Cycles

Specimen	Specimen Number	Electrode Spacing (Inches)	Per Cent Difference			
			$\frac{V(60) - V(400)}{V(60)} \times 100$			
			Altitude (Feet)*			
			0	15,100	30,300	45,200
Air-Gap Breakdown						
Parallel straight relay strips, Figure 1B	{ 1.....	0.187.....	2.9.....	-3.8.....	3.8.....	-3.7.....
	{ 2.....	0.187.....	0.4.....			9.8.....
Parallel L-shaped relay strips, Figure 1C	{ 1.....	0.117.....	-2.0.....	7.9.....	4.8.....	7.7.....
	{ 2.....	0.117.....	0.6.....			-5.0.....
Creepage Breakdown (Nonuniform Field)						
Textolite, Figure 2B.....	{ 1.....	0.125.....	0.3.....	8.0.....	0.....	-13.0.....
	{ 2.....	0.125.....	-0.3.....	0.9.....	-0.6.....	-19.1.....
	{ 3.....	0.125.....	0.3.....			-24.6.....
	{ 4.....	0.125.....	1.8.....			-13.3.....
Textolite, Figure 2C.....	{ 1.....	0.035.....	-8.2.....	-8.7.....	-10.4.....	1.4.....
	{ 2.....	0.035.....	-3.0.....	-2.3.....	-1.0.....	5.1.....
	{ 3.....	0.035.....	1.9.....			-2.6.....
	{ 4.....	0.035.....	5.4.....			2.7.....

* Corresponds to pressures existing at the specified altitude, but not to temperatures. Temperature held at 72 degrees Fahrenheit.

Table II. Effect of High Humidity on the Creepage Breakdown Potential of Precooled Specimens

Specimen	Specimen Number	Electrode Spacing (Inches)	Number of Tests	Per Cent Difference			
				Min (A)* - Min (B)**		Avg (A)* - Avg (B)**	
				Min (A)		Avg (A)	
				Altitude (Feet)†		Altitude (Feet)†	
				0	45,200	0	45,200
Textolite, Figure 2B..	1.....	0.125	3	25.3	28.6	16.0	2.0
	2.....	0.125	2	32.1	18.8	20.2	15.5
	3.....	0.125	1	22.0		1.4	
	4.....	0.125	1	21.8		10.2	

* (A) Breakdown potential of a dry specimen.

** (B) Breakdown potential of a specimen subjected to special moisture conditions.

† Corresponds to pressures existing at the specified altitude, but not to temperatures. Temperature held at 72 degrees Fahrenheit.

the average high potential breakdown at 60 cycles for different specimens having the same dimensions and constructed of the same materials have exceeded 25 per cent. Since 64 per cent of the differences are less than $\pm$ five per cent and 86 per cent less than $\pm$ ten per cent, it seems justifiable to conclude that there is no appreciable difference between 60- and 400-cycle high-potential breakdown values for the range of electrode spacings used.

Similar conclusions may be drawn on the effect of humidity on high-potential air-gap and creepage breakdown values. A comparison between tests performed with 20 per cent relative humidity and with 85 per cent relative humidity at 72 degrees Fahrenheit for reduced pressures corresponding to various altitudes showed that 50 per cent of the differences between the average breakdown values (average of ten readings) at 20 per cent humidity and 85 per cent humidity, divided by the average breakdown values at 20 per cent humidity are less than $\pm$ five per cent, and 80 per cent are less than $\pm$ ten per cent. These results indicate that humidity has inappreciable effect on air-gap breakdown potential characteristics and on creepage breakdown potential characteristics for the materials tested.

Tests which were conducted on specimens which had been cooled to 0 degrees Fahrenheit and then placed in a high humidity atmosphere (85 per cent) at 72 degrees Fahrenheit showed that moisture condensed on the surfaces of the specimens. The moisture lowered the initial creepage breakdown potential of a specimen, but successive breakdowns dried the surface sufficiently to raise the breakdown potential to its average dry value. It should be pointed out that if the electric circuit is such that an arc can follow the initial spark, then the surface of the insulation is usually carbonized by the arc to such an extent that a permanent

short circuit is created between the electrodes. Since repeated flashovers raise the breakdown potential nearly to the dry breakdown potential, then the per cent difference between the minimum breakdown potential of a dry specimen and the minimum breakdown potential of the same specimen when treated as already stated is more important than the per cent difference between the average values of the dry specimen and the treated specimen. Table II shows the per cent difference for both the minimum and average values. Ten readings were obtained for each test, from which the minimum and average values were obtained. Sometimes more than one test was performed on a specimen, and, when such was the case, the minimum and average values were obtained from the

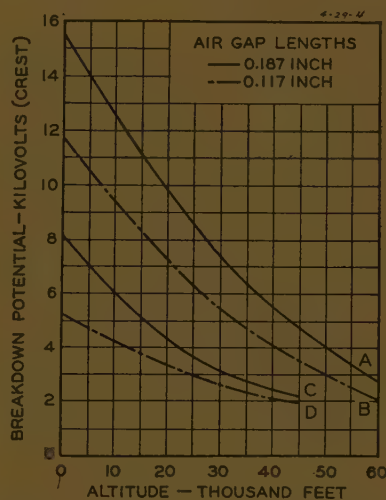


Figure 4. Comparison of air-gap breakdown between parallel strips with air-gap breakdown between hemispheres

A-B. $\frac{1}{4}$ -inch-diameter brass hemispheres. Air temperature 72 degrees Fahrenheit
C. Parallel straight silver-plated phosphor-bronze strips, 0.010 inch thick. Air temperature 72 degrees Fahrenheit
D. Parallel L-shaped silver-plated phosphor-bronze strips, 0.031 inch thick. Air temperature 72 degrees Fahrenheit

(See Figure 1 for picture of specimens)

total number of readings. It was found from experimental tests that the initial breakdown potential of ceramic specimens when subjected to this special moisture condition could be raised about 25 per cent by treating the ceramic with the vapors of silicon methyl chloride (a silicone derivative). This treatment produces a ceramic surface which is water repellant and which has a very high electrical surface resistivity under dew-point conditions.

Breakdown potential values under various conditions are shown in Figures 3, 4, and 5. Figure 3 shows the hemisphere-gap breakdown characteristics for different electrode spacings. It also shows the effect of reduced temperatures on the breakdown characteristics based on theoretical analysis. Figure 4 compares the air-gap breakdown characteristics between hemispheres with the air-gap breakdown characteristics between various aircraft relay parts. Figure 5 makes a similar comparison between creepage breakdown in a uniform and nonuniform electrostatic field.

From curves similar to Figures 3, 4, and 5, a table showing the ratio of breakdown potential at sea level to a pressure corresponding to 45,000 feet elevation for an air temperature of 72 degrees Fahrenheit for both air-gap and creepage breakdown has been compiled. Table III shows this ratio. This ratio is important in determining equivalent sea-level high-potential voltage values to correspond to altitude high-potential values. If the AIEE specification requiring electrical equipment to withstand a high-potential

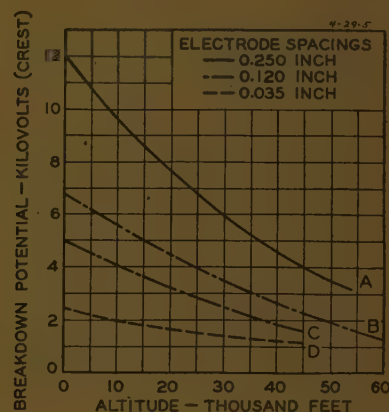


Figure 5. Comparison between creepage breakdown in a uniform electrostatic field and creepage breakdown in a nonuniform electrostatic field

A-B. Breakdown across Textolite surface located in a uniform field. Air temperature 72 degrees Fahrenheit
C-D. Breakdown across Textolite surface located in a nonuniform field. Air temperature 72 degrees Fahrenheit

(See Figure 2 for picture of specimens)

Table III. Ratio of Breakdown Potential at Sea Level to 45,000 Feet*

	Ratio V(0) to V(45,000)
Air-Gap Breakdown	
Hemisphere gap $\left\{ \begin{array}{l} 1/12\text{-inch spacing} \dots\dots\dots 3.5 \\ 1/8\text{-inch spacing} \dots\dots\dots 3.4 \\ 1/4\text{-inch spacing} \dots\dots\dots 3.3 \\ 1/2\text{-inch spacing} \dots\dots\dots 3.3 \end{array} \right.$	
Parallel straight strips—0.187-inch gap	3.7
Parallel L-shaped strips—0.117-inch gap	2.7
Creepage Breakdown	
Uniform field	
Textolite $\left\{ \begin{array}{l} 1/8\text{-inch thick (arc with grain)} \dots\dots 3.4 \\ 1/4\text{-inch thick (arc with grain)} \dots\dots 3.0 \\ 1/8\text{-inch thick (arc across grain)} \dots\dots 3.0 \\ 1/4\text{-inch thick (arc across grain)} \dots\dots 2.8 \end{array} \right.$	
Cold-molded asbestos compound $\left\{ \begin{array}{l} 1/8\text{-inch thick} \dots\dots\dots 2.8 \\ 1/4\text{-inch thick} \dots\dots\dots 3.0 \end{array} \right.$	
Nonuniform field	
Hot-molded compound (Bakelite material 1132) 0.13-inch spacing	3.5
Textolite $\left\{ \begin{array}{l} 0.125\text{-inch spacing} \dots\dots\dots 3.1 \\ 0.035\text{-inch spacing} \dots\dots\dots 2.1 \end{array} \right.$	

* Corresponds to pressures existing at the specified altitude, but not to temperature. Temperature held at 72 degrees Fahrenheit.

voltage of twice rated voltage plus 1,000 volts is to apply at 45,000 feet, then the same equipment will have to withstand from 2.7 to 3.7 times as high a voltage at sea level. On 208-volt circuits, the equipment would have to withstand 1,416 volts at 45,000 feet and from 3,820 to 5,240 volts at sea level. Such a specification is rather severe under such conditions, and it would seem that a more satisfactory specification would be to require an equivalent sea-level voltage of 2.7 to 3.7 times twice rated voltage plus an additional 1,000 volts. On 208-volt equipment, the equivalent sea-level voltage would then be from 2,122 to 2,540 volts.

Comparison With Theoretical Performance

Experimental tests made by Peek¹ indicate that the breakdown voltage between spheres is independent of the frequency, provided corona is not present before breakdown to provide a considerable space-charge effect. He also determined from experimental tests² that, for spheres, corona does not appear before breakdown until the spacing between

the spheres equals eight times the radius of the sphere. The maximum spacing-radius ratio for the hemispheres was four (1/2-inch gap, 1/8-inch radius). The theory, therefore, seems to check the data that breakdown characteristics for hemisphere gaps are the same at 60 and 400 cycles.

The effect of humidity on air-gap breakdown for sphere gaps is inappreciable if the surfaces remain dry,³ while the effect of humidity on needle gaps is to require a higher voltage to cause breakdown when the humidity is high than when it is low.⁴ These two conditions correspond somewhat to the hemisphere gap and the air gap between various parts of relays, respectively. However, no humidity effect was observed on gaps between various relay parts.

In order to check the effect of reduced temperatures on the breakdown characteristics of air gaps, use was made of the principle of similitude.⁴ This principle, which was developed by Townsend, states that, for geometrically similar systems, the breakdown potential is a function of only the product of gas density and one of the linear dimensions of the system, provided no space-charge effect is present before breakdown. Since the gas density is directly proportional to the gas pressure and inversely proportional to the gas temperature, then an equation expressing these statements will be

$$E=f(\rho \times d)=f_1\left(\frac{P}{T} \times d\right)$$

where *E* is the breakdown potential, ρ the gas density, *T* the absolute gas temperature, *P* the absolute gas pressure, and *d* the linear dimension of the system.

To convert breakdown characteristics at room temperatures to temperatures corresponding to various altitudes, the value of *P/T* must remain constant if *E* and *d* are held fixed. By reading the value of *E* corresponding to some pressure and 72 degrees Fahrenheit from the experimental curves of Figures 3 and 4, and calculating the *P/T* ratio, a new value of *P* and *T* corresponding to some altitude can be picked which will give the

same *P/T* ratio. The value of *E* will then apply to the new temperature and pressure conditions which are the true conditions existing at that altitude. Figure 3 shows curves calculated in this manner.

Conclusions

The following conclusions may be drawn from the data presented:

1. Air-gap and creepage breakdown characteristics are substantially the same for 60- and 400-cycle supply for short gaps.
2. The effect of a very humid atmosphere on air-gap and creepage breakdown potentials is inappreciable, provided there is no moisture condensation on the electrodes or the dielectric.
3. About 25 per cent reduction in the initial creepage breakdown potential can be expected if there is appreciable moisture condensation on the surface of the dielectric. Succeeding breakdown values will approach gradually the flashover value for the dry dielectric, provided the surface does not become carbonized.
4. Treating ceramic parts with a silicone vapor will raise the initial creepage breakdown about 25 per cent if there is considerable moisture condensation on the surface of the ceramic.
5. Breakdown characteristics obtained on aircraft relay and contactor parts may differ as much as 100 per cent from characteristics obtained from sphere-gap observations for air-gap breakdown or from uniform-field breakdown observations for creepage breakdown.
6. The ratio of air-gap or creepage breakdown potential at sea level to pressures corresponding to 45,000 feet varies from 2.7 to 3.7, depending upon the electrode shape and spacing for air-gap breakdown, and on the dielectric material and the electrostatic field distribution between the electrodes for creepage breakdown.

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High-Voltage Oil Circuit Breakers for Rapid Reclosing Duty

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Synopsis: Experience has shown that high-speed reclosing of circuit breakers on high-voltage transmission lines is of considerable value in maintaining system stability and continuity of service. This paper describes a new line of outdoor oil circuit breakers and the special design features which make them suitable for 20- and 35-cycle reclosing duty at voltages as high as 230 kv. Data are included showing high-power-laboratory short-circuit tests on these duty cycles at 138 kv and 230 kv at currents corresponding to a three-phase duty of more than 2,500,000 kva.

THE present emergency demands the highest possible reliability in the electrical systems which are supplying unprecedented loads to industrial centers. In many locations the use of high-speed reclosing of high-voltage circuit breakers has proved to be of great value in maintaining continuity of service. System-stability requirements have brought about the development of high-speed circuit breakers in the voltage range from 115 kv to 287 kv with an interrupting time of five or even three cycles. In recent years, a few of these high-speed breakers have been available with provision for high-speed reclosing. This paper describes the design and performance of a line of high-voltage circuit breakers particularly designed to meet these severe operating requirements.

Because of the arc-interrupting effectiveness and low arc energy of multifold deion grid contacts described in a paper before the Institute a year ago,¹ it is possible for the physical size of these high-voltage reclosing circuit breakers to be smaller than the older standard breakers. Simplification of the operating mechanism is made possible by utilizing the recently developed compressed-air type of mechanism for operating high-voltage oil circuit breakers.² Short-circuit tests made in the high-power laboratory have demonstrated the ability

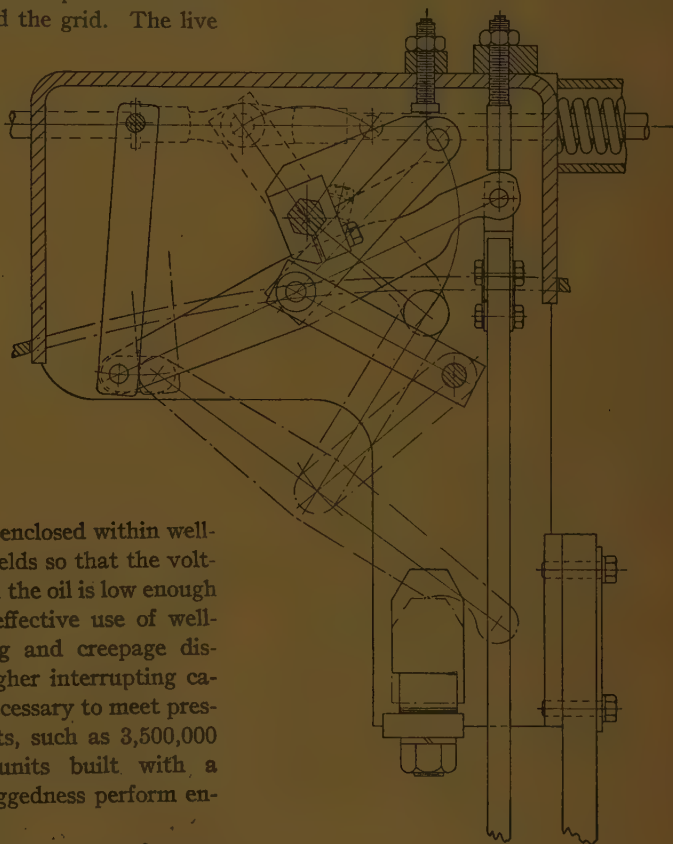
Paper 44-37, recommended by the AIEE committee on protective devices for presentation at the AIEE winter technical meeting, New York, N. Y., January 24-28, 1944. Manuscript submitted November 26, 1943; made available for printing December 10, 1943.

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of these new circuit breakers to interrupt on either a 35-cycle or a 20-cycle reclosing duty cycle short-circuit powers as high as 2,500,000 kva.

The new interrupter for these oil circuit breakers, called the multifold deion grid, is smaller in size than earlier forms of contacts. From the nature of its operation the arcs are kept under control at all times, and the evolution of gas is so reduced that very little space is needed for insulation around the grid. The live

Figure 1. Pole-unit lever system for 138-kv breaker, showing relation of toggles, stops, dashpot, and accelerating spring



parts are compactly enclosed within well-rounded metallic shields so that the voltage gradient through the oil is low enough to allow the most effective use of well-co-ordinated striking and creepage distances. For still higher interrupting capacities which are necessary to meet present-day requirements, such as 3,500,000 kva, interrupting units built with a greater degree of ruggedness perform entirely satisfactorily.

The bushing-type current transformers are built to modern American Standards Association and National Electrical Manufacturers Association standards. The standard design of one current transformer per bushing fulfills usual requirements, although ample space can be made available to provide for two transformers per bushing where required, either multiratio on the Hipersil core for relaying purposes or single ratio on the Hipernik core for high-accuracy metering service. The small bushing diameter is also an advantage here, as it permits plenty of space for the transformers without making necessary the use of

protruding casings to mar the otherwise smooth-walled tank.

The new line of breakers presented an opportunity to make a new design of pole-unit levers, better adapted to high-speed operation. The general features required for straight line motion which have been used for so many years have been retained, but, with the more effective interrupters, it is now possible to reduce the length of travel and yet keep ample toggle effect at the closed position of the contacts. Fabricated steel levers and links are used throughout as shown in Figure 1. The load characteristic (Figure 2) gives the various increments of load for the entire closing stroke, plotted against mechanism pull-rod travel. In other words, each static load inside the three tanks, such as the

dead weight of the contacts and levers, and the contact-spring load is multiplied by the pull ratio, to convert it into equivalent load at the operating mechanism. Since the accelerating spring for the mechanism illustrated is outside the tank, it is added without being modified by the pull ratio. A summation of these increments shows a net load increasing from slightly over 1,000 pounds at the open position, to a little over 3,000 pounds at the closed position, all of which is well within the ability of either the conventional solenoid or pneumatic mecha-

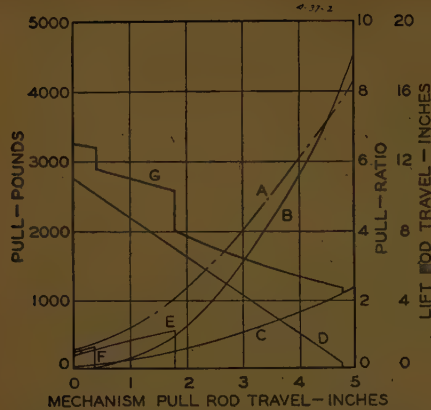


Figure 2. Load curve for three-pole 138-kv breaker

- A. Pull ratio of levers showing greatest mechanical advantage at closed position of stroke
- B. Relation of lift-rod travel to operating-mechanism travel
- C. Equivalent weight of pole-unit levers, contacts, and so forth, expressed as equivalent mass at the operating mechanism
- D. Accelerating spring load in pounds
- E. Intermediate contact load
- F. Main contact load
- G. Total load on operating mechanism. Summation of C-D-E-F

nism. In this class of breaker the added load due to forces encountered in closing against fault currents is negligible and hence can be neglected.

Compressed-Air Operating Mechanism

A schematic view of the compressed-air operating mechanism, suitable for high-speed reclosing, is illustrated in Figure 3. The operating system is connected at all times to the main-breaker operating rod, only one lever being required for latching purposes. During the closing operation, air is admitted to the top of the cylinder, forcing the piston down to the closed position where it is held by the latch. Energizing the trip coil also operates a large "dump valve" arranged so that any air left in the cylinder on the top side, as for example on immediate

tripout after closing, will be exhausted sufficiently rapidly to give full opening speed. The acceleration on opening is provided entirely by springs so that even in the event of failure of the compressed-air system, the breaker could perform its protective function of clearing the circuit. To obtain rapid reclosing it is necessary to time the opening of the valve admitting air to the cylinder such that the breaker will be brought to rest before the normal full-open position but with ample margin for interrupting the arc, and returned to the closed position within the required time. A record of a timing test showing an open-close-open operation is illustrated in Figure 4. It is to be noted that the velocity of contact opening is essentially the same on the second tripping as on the first, illustrating the effectiveness of the dump valve in giving pneumatically trip-free operation as an alternative to mechanically trip-free operation.

Multiflow Deion Grids for High-Speed Reclosing

Oil circuit breakers used on automatic reclosing duty cycles are subject to certain standard derating factors according

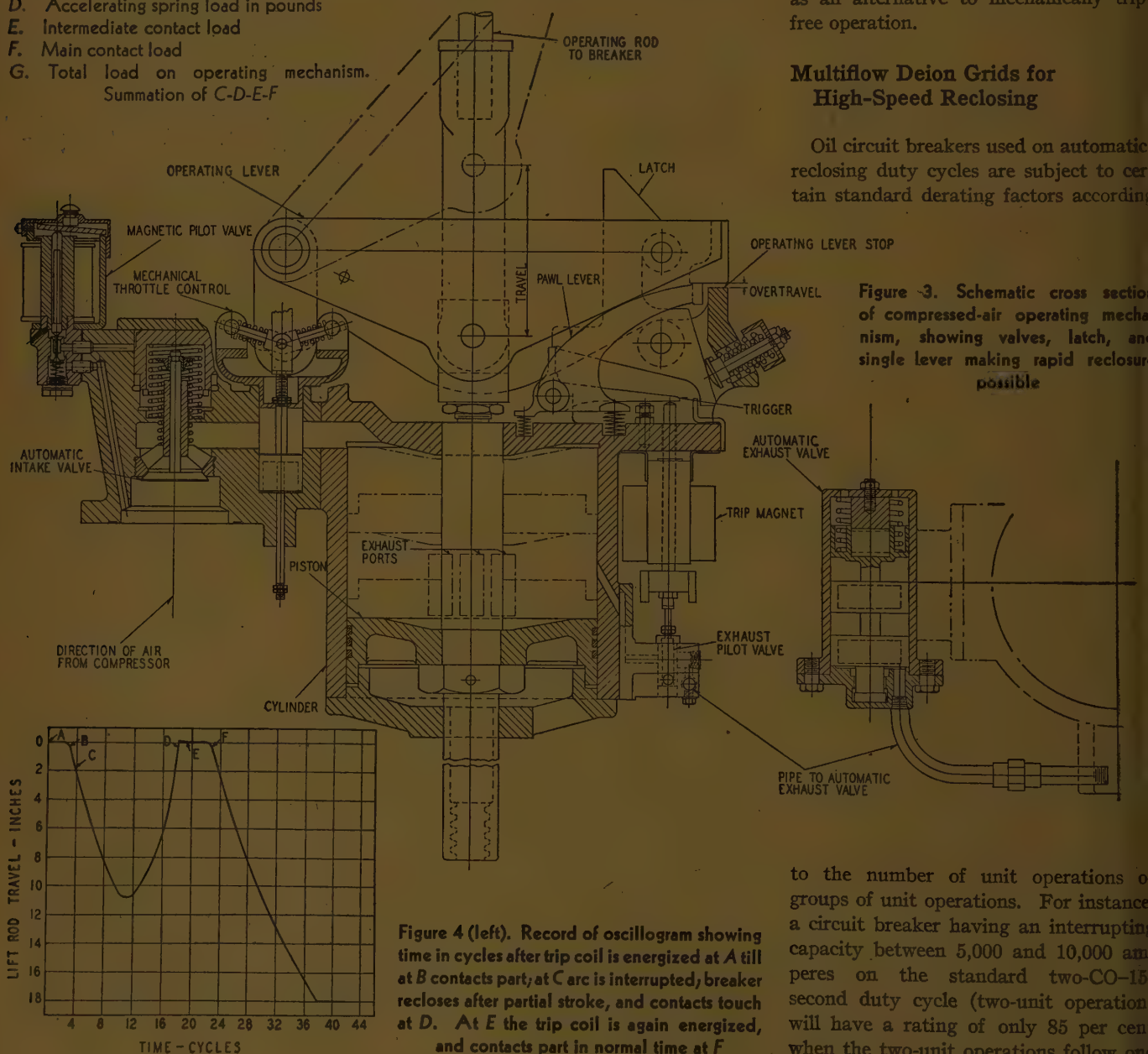


Figure 3. Schematic cross section of compressed-air operating mechanism, showing valves, latch, and single lever making rapid reclosing possible

Figure 4 (left). Record of oscillogram showing time in cycles after trip coil is energized at A till at B contacts part, at C arc is interrupted, breaker recloses after partial stroke, and contacts touch at D. At E the trip coil is again energized, and contacts part in normal time at F

to the number of unit operations or groups of unit operations. For instance a circuit breaker having an interrupting capacity between 5,000 and 10,000 amperes on the standard two-CO-15 second duty cycle (two-unit operation) will have a rating of only 85 per cent when the two-unit operations follow one

Table 1. 230-Kv Three-Cycle Breaker Test
(Two Grids Per Pole)

a. One Grid, 1/2 Pole, 66 Kv to Ground, Charging Current, 60 Cycles

Test Number	Interrupted Current (Amperes)	Arcing Time (Cycles)	Main Gap Per Grid (Inches)	*Interrupting Time (Cycles)
1.....	45.....	1.0.....	2.1.....	2.4.....
2.....	45.....	1.1.....	2.45.....	2.5.....
3.....	45.....	1.2.....	2.8.....	2.6.....
4.....	45.....	1.3.....	3.15.....	2.7.....
5.....	45.....	1.4.....	3.5.....	2.8.....
6.....	45.....	1.2.....	2.8.....	2.6.....
7.....	90.....	1.6.....	4.2.....	3.0.....
8.....	90.....	1.5.....	3.85.....	2.9.....
9.....	90.....	1.15.....	2.6.....	2.5.....
10.....	90.....	1.3.....	3.15.....	2.7.....
11.....	90.....	1.5.....	3.85.....	2.9.....
12.....	90.....	1.5.....	3.85.....	2.9.....
13.....	180.....	1.3.....	3.15.....	2.7.....
14.....	180.....	1.0.....	2.1.....	2.4.....
15.....	180.....	1.1.....	2.45.....	2.5.....
16.....	180.....	1.4.....	3.5.....	2.8.....
17.....	180.....	1.2.....	2.8.....	2.6.....
18.....	180.....	1.4.....	3.5.....	2.8.....

b. Two Grids, 132 Kv to Ground, Charging Current, 60 Cycles

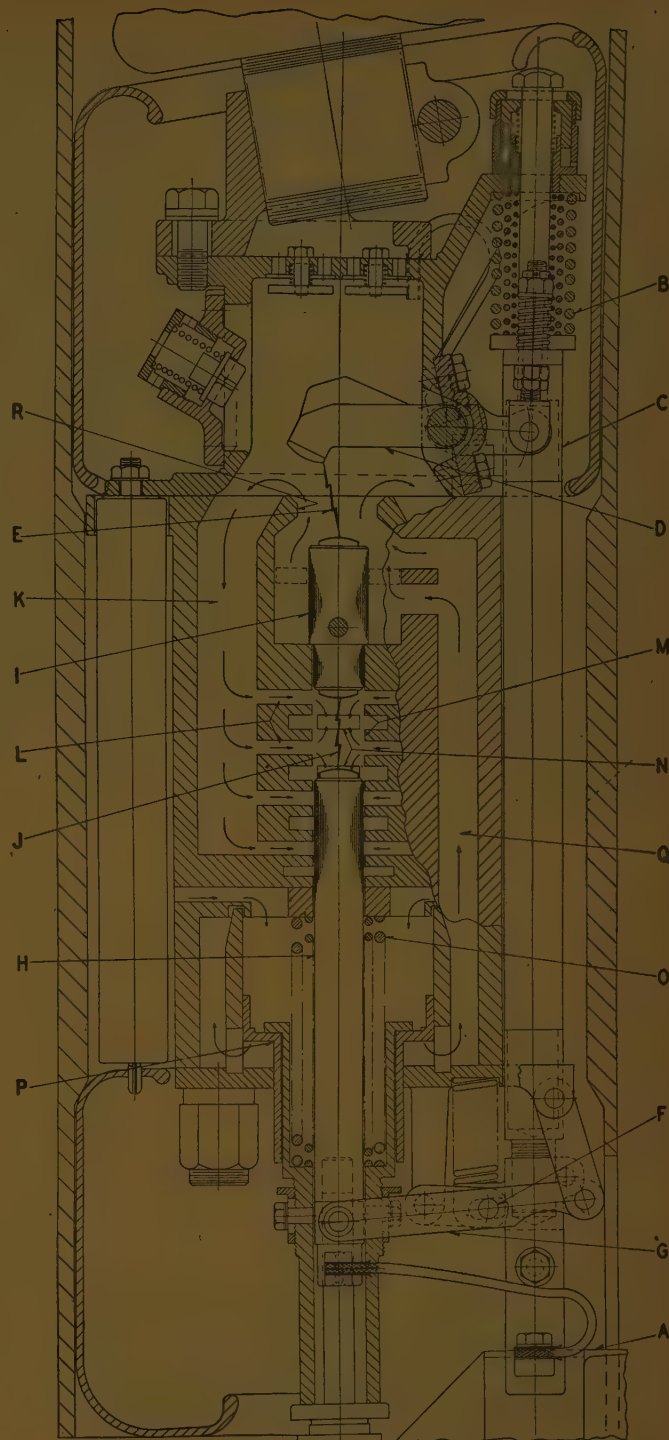
Test Number	Interrupted Current (Amperes)	Arcing Time (Cycles)	Main Gap Per Grid (Inches)	*Interrupting Time (Cycles)
1.....	90.....	1.4.....	3.5.....	2.8.....
2.....	90.....	1.4.....	3.5.....	2.8.....
3.....	90.....	1.3.....	3.15.....	2.7.....
4.....	90.....	1.0.....	2.1.....	2.4.....
5.....	90.....	1.2.....	2.8.....	2.6.....
6.....	90.....	1.0.....	2.1.....	2.4.....

*Based on time of 1.4 cycles from energizing trip to parting of contacts.

another with no intentional time delay. These derating factors have been standardized in an attempt to take into consideration certain residual effects, such as temperature of the contact, accumulation of gas and carbon which may make the second interruption more difficult than the first. It is obvious that these residual effects will be minimized in proportion as the arcing time and arc energy are reduced. This result is accomplished in two ways by the multiflow-deion grid type of circuit interrupter. First, the pressure-generating arc and the interrupting arc in the higher-voltage breakers are drawn simultaneously, and second, the arc is deionized, without unnecessary lengthening, by a multiplicity of radially flowing streams of oil. Figure 5 shows a cross section of the latest design of multiflow deion grid for three-cycle operation at 230 kv. In addition to the normal multiflow deionizing action an auxiliary oil-flow piston is provided to help interrupt line-charging current without delayed restriking and also to provide flushing action when interrupting high fault currents. With regard to the first function of this auxiliary piston, it

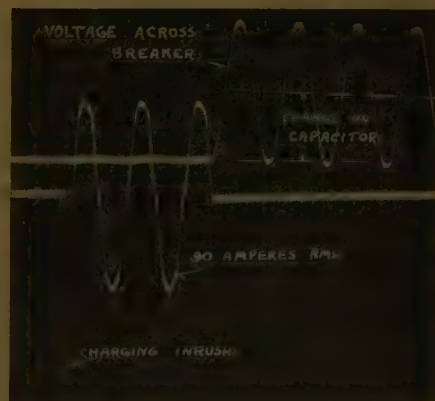
Figure 5. 230-kv multiflow deion grid for three-cycle operating time and 2,500,000-kva rupturing capacity

Tripping of breaker releases main cross-arm A, allowing springs B to move operating-rod C down and to rotate contact arm D, drawing pressure-generating arc E. Simultaneously, pin F swings lever G downward, pulling contact H away from intermediate contact I to draw main arc J. Pressure from upper arc E drives oil through channel K to multiflow inlets L, deionizing arc in multiorifice structure M and sending arc products out vents N. Springs O push piston P downward to provide supplementary oil flow for low-current arc interruption, flowing oil through channel Q to orifice R in upper gap and then to main flow channel. Back pressure from high-current arcs stops piston until arc is interrupted, when completion of stroke sends flushing oil flow through grid



is well known that successive restriking during the interruption of transmission-line-charging current or the charging current to a large capacitor installation may, under unfavorable conditions, give rise to excessive overvoltage. However circuit breakers equipped with multiflow deion grids, which without piston may show one or occasionally two restrikes, actually did not develop more than twice normal voltage on field tests.

Figure 6. Oscillogram of charging current interruption at 66 kv on 230-kv three-cycle multiflow deion grid unit



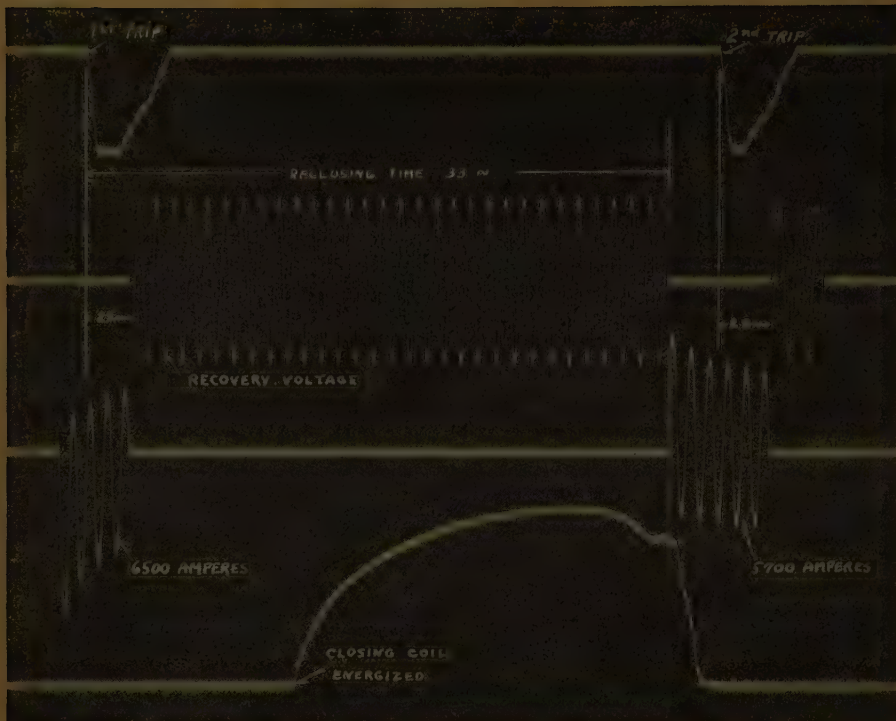


Figure 7. Oscillogram of 230-kv multiflow deion grid interruption at 132 kv to ground on 35-cycle reclosing duty

Fault equivalent to 2,500,000 kva, three phase, opened twice with interrupting time less than three cycles on each tripping operation

Transients of this magnitude may be encountered in any case during the energizing of a line or interrupting fault currents.

When only two interrupting units per pole for 230 kv were used, it was found that the contact separation at the end of one-half cycle after contact parting was insufficient to hold double normal

voltage even with the gap completely filled with clean oil. The piston was, therefore, arranged with a delayed pickup so that oil flow is not started until after the contacts have opened approximately one inch. At the next current zero, the charging current is extinguished, and the insulation established in the contact gap becomes adequate to prevent restriking of the arc. Note from Figure 5 that the oil flow from the piston is directed through a single orifice in the top break to develop additional dielectric strength in this gap before passing into the channels to the multiorifice structure in the main break. In Table I are listed 18

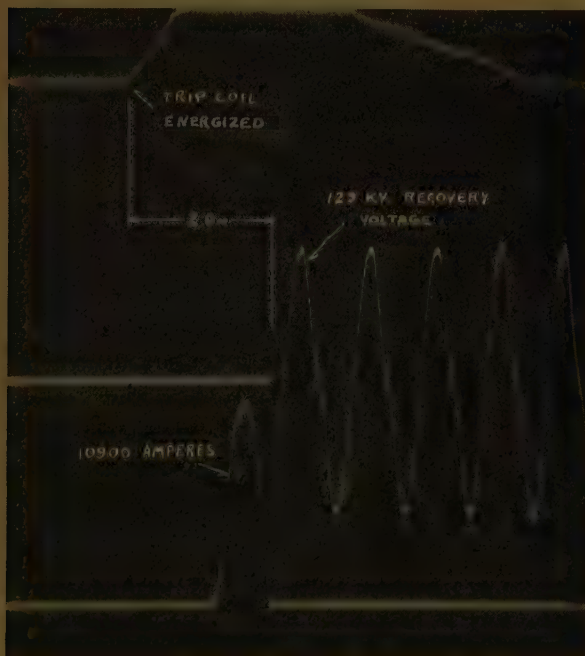


Figure 8. Oscillogram of 230-kv multiflow deion grid interruption at 132-kv-to-ground clearing fault equivalent to 4,300,000 kva, three phase, within two cycles after energizing trip coil using only two grid units per breaker pole

Table II. 230-Kv Three-Cycle Breaker Tests (Two Grids Per Pole)

(a). 132 Kv to Ground, 35-Cycle Reclosing Duty Cycle

Test Number	Interrupted Current (Amperes)		Interrupting Time (Cycles)		*Re-closing Time (Cycles)
	1st Interruption	2nd Interruption	1st Interruption	2nd Interruption	
1	4,050	4,050	2.6	2.6	33
2	3,950	3,800	2.8	2.8	32
3	4,150	4,150	2.8	2.8	33
4	6,500	5,700	2.5	2.8	33
5	6,200	5,700	2.8	2.9	33
6	6,200	5,600	2.3	2.9	34
7	3,350	2,900	2.8	3.0	33
8	3,500	3,050	2.8	3.0	33

(b). 132 Kv to Ground, Single Opening Tests

Test Number	Interrupted Current (Amperes)	Interrupting Time (Cycles)	Equivalent 230 Kv, Three-Phase Kva
1	5,300	2.35	2,100,000
2	5,600	2.3	2,220,000
3	5,300	2.5	2,100,000
4	6,200	2.2	2,450,000
5	10,900	2.0	4,300,000
6	8,800	2.4	3,500,000

198 Kv to Ground (Corresponds to Ungrounded Line Condition)

7	4,100	2.9	1,620,000
8	4,600	3.0	1,820,000
9	6,300	2.9	2,500,000

* Time from initially energizing trip coil to re-establishment of circuit on reclosing stroke.

interruptions of charging currents with 45, 90, and 180 amperes at 66,000 volts across a single grid unit, and also six interruptions of 90 amperes at 132,000 volts across two grids. No delayed restrikes occurred on any of these tests, a typical oscillogram being shown in Figure 6.

When short-circuit currents are interrupted, the pressure developed by the arc within the interrupting unit is greatly

Table III. 230-Kv Five-Cycle Breaker Tests 132 Kv to Ground, 35-Cycle Reclosing Duty Cycle

Test Number	Interrupted Current (Amperes)		Interrupting Time (Cycles)		*Re-closing Time (Cycles)
	1st Interruption	2nd Interruption	1st Interruption	2nd Interruption	
1	2,100	1,800	2.9	3.8	31.5
2	2,100	1,900	3.3	3.0	31.0
3	2,050	1,850	3.4	4.0	31.5
4	5,050	3,850	3.0	3.6	32.5
5	4,650	3,900	3.0	3.1	32.0
6	5,050	3,800	3.0	3.8	32.0
7	7,050	5,500	2.8	3.2	31.5
8	7,000	5,600	2.9	3.6	31.5
9	6,600	5,400	2.9	3.4	31.0

* Time from initially energizing trip coil to re-establishment of circuit on reclosing stroke.

excess of the spring pressure provided behind the small oil-flow piston. The piston, therefore, does not function during the arc-rupturing process, but, after the circuit has been cleared and the pressure within the unit falls to a relatively low value, the piston then completes its delayed stroke, scavenging the entire arcing space in both contact breaks with a flow of clean oil. Even on a 20-cycle reclosing duty cycle there is sufficient time for this action to be completed so that when the breaker is reclosed, the deion grid is in substantially the same condition as it would be on an initial interruption.

The oscillogram shown in Figure 7 is rather remarkable in that it shows what is believed to be the first interruption of a current corresponding to a three-phase fault of 2,500,000 kva at 230 kv on a 35-cycle reclosing duty cycle, each interruption being accomplished in less than three cycles from energizing the trip coil. Of particular interest is the fact that this test was made with only two interrupting units in a 72-inch tank. This was one of a series of eight consecutive high-power reclosing tests listed in Table II. Also included in this table are nine tests showing the interrupting performance on single opening operations with 132 kv and with 98 kv across a single pole. The interruption of 10,900 amperes shown in Figure 8 is equivalent to a three-phase rounded fault of 4,300,000 kva, this tremendous power being cleared in the remarkably short time of only 2.0 cycles after energizing the trip coil. The 198-kv tests followed without examining the contacts, which were found at the end of the series to have suffered surprisingly little deterioration with considerable life still remaining.

In Figure 9 is the oscillogram of a 35-cycle-reclosing-duty-cycle test on a 230-kv breaker using a multiflow deion grid or five-cycle interrupting time. This grid shown in Figure 10a, differs from the three-cycle design in that there is no multiplying lever system for the moving contact and no auxiliary piston is provided for low current interruption or scavenging action. The excellent performance illustrated by the series of tests in Table III gives evidence that on the 35-cycle reclosing duty cycle, and, with relatively high-speed arc extinction, highly satisfactory performance is obtained.

However, for the 20-cycle reclosing duty cycle, insufficient time is available for the gas produced from the first interruption to be dissipated completely before the breaker is reclosed, and with-

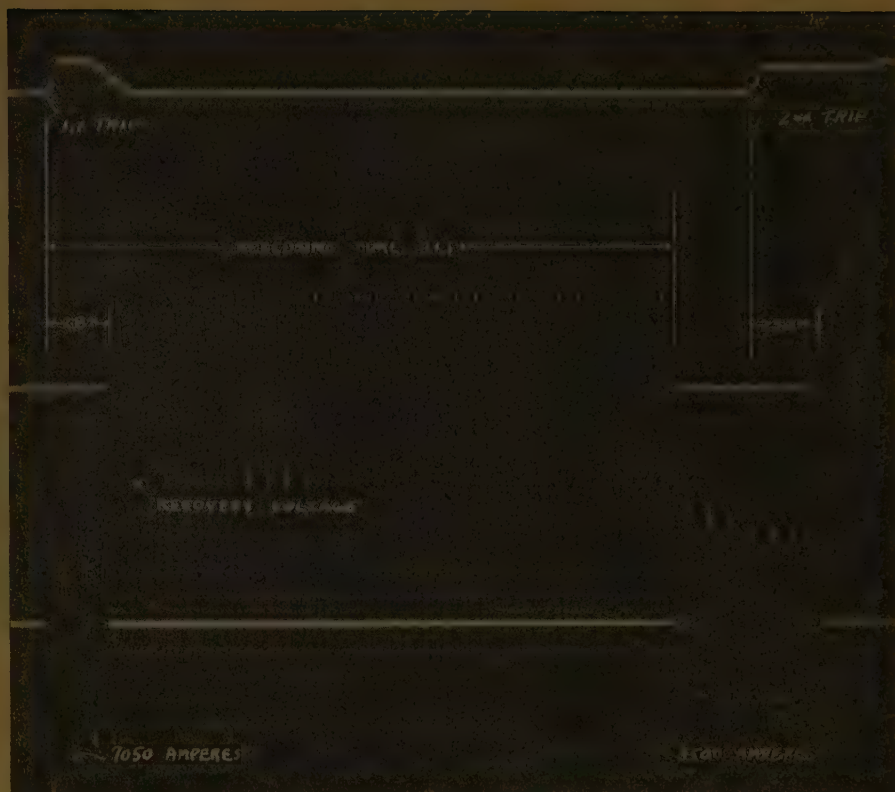


Figure 9. Oscillogram of 230-kv five-cycle multiflow-deion-grid breaker pole-unit opening fault at 132 kv to ground, equivalent to 2,800,000 kva, three-phase, on 35-cycle reclosing duty.

out the flushing action of the piston there would be a tendency, particularly in the higher-voltage breakers, for the arc to sparkover through the contact gap during the closing part of the stroke and impair the interrupting effectiveness of the second operation.

At 138 kv the voltage gradient during a closing operation is considerably less than in a 230-kv breaker, and satisfactory reclosing performance has been obtained without a special oil-flushing arrangement. As far back as two years ago, field tests were made on a 132-kv oil circuit breaker with an older design of deion-grid contact operating on a 30-cycle reclosing duty.³ These tests were made at currents up to 3,000 amperes or approximately 750,000 kva.

The multiflow deion grids for five-cycle service at 138 kv utilize the simplified consecutive contact-opening design illustrated by Figure 10b. A special laboratory test connection was used, supplying 44-kv three-phase power to the single-pole unit, the third phase being brought into the breaker moving contact crossbar by a flexible connection fastened to the bottom of the tank. In this way 44 kv was applied to the deion grid on each terminal, the two in series normally being subjected to 76 kv, or line-to-ground

potential on a 132-kv system. The oscillogram in Figure 11 shows a short-circuit current of 9,000 amperes successfully interrupted on a 20-cycle-reclosing duty-cycle test corresponding to approximately 2,250,000 kva. The arcing time on both of these tests was approximately three cycles. No better evidence of the exceptionally low arc energy and gas generation in the multiflow deion grids under short-circuit conditions would seem to be required than the excellent results obtained on this very severe rupturing duty. However, a further striking demonstration of the low stress in the breaker tank was obtained by balancing a 1/2-inch bolt six inches long on its head on a board clamped in a

Table IV. 138-Kv Five-Cycle Breaker Tests
44 Kv Applied to Grid on Each Terminal

Test Num- ber	Interrupted Current (Amperes)		Interrupting Time* (Cycles)		Equi- valent 132 Kv Three- Phase Kva
	Grid A	Grid B	Grid A	Grid B	
1...	5,300...	3,900...	4.3...	4.6...	1,220,000
2...	5,800...	4,200...	4.6...	4.9...	1,340,000
3...	5,500...	7,500...	4.3...	4.0...	1,720,000
4...	6,300...	7,500...	4.5...	4.2...	1,720,000
5...	5,800...	7,500...	4.3...	4.6...	1,720,000
6...	8,000...	8,900...	4.1...	4.9...	2,050,000
7...	8,000...	9,200...	4.1...	4.2...	2,100,000
8...	9,200...	8,900...	4.3...	4.5...	2,100,000
9...	10,300...	11,500...	4.3...	4.5...	2,650,000
10...	9,700...	11,500...	4.5...	4.7...	2,650,000
11...	18,300...	15,500...	4.3...	4.1...	4,200,000

* Based on time of 2.3 cycles from energizing trip coil to parting of contacts.

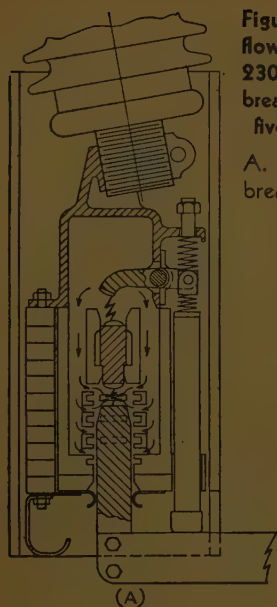
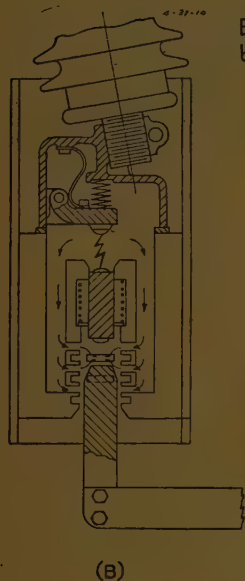


Figure 10. Multiflow deion grids for 230-kv five-cycle breaker and 138-kv five-cycle breaker

A. 230-kv five-cycle breaker, multiorifice grid assembly



B. 138-kv five-cycle breaker, multiorifice grid assembly

level position on top of the breaker tank. Single opening tests were carried up to short-circuit currents of as high as

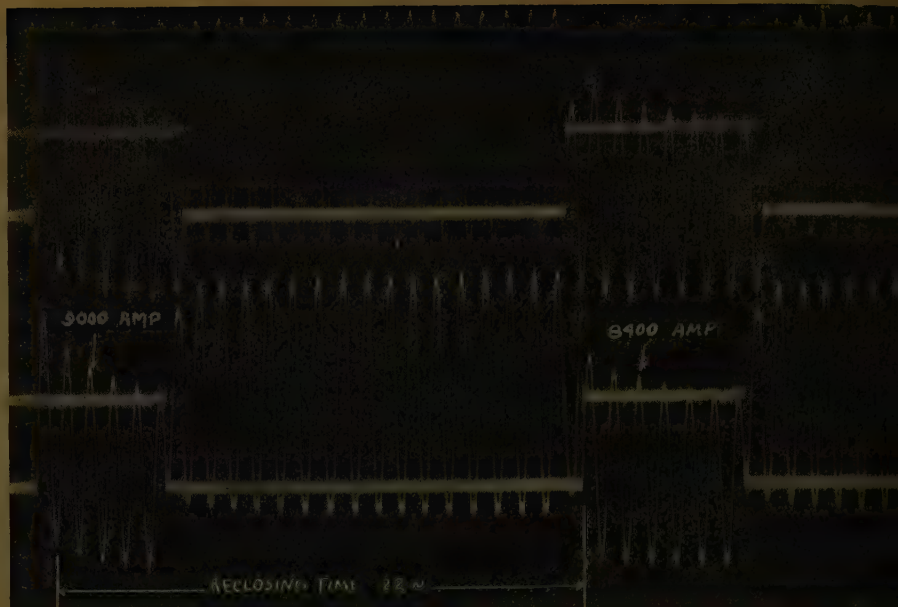


Figure 11. Oscillogram of 138-kv five-cycle multiflow-deion-grid-breaker pole-unit opening fault at 44 kv across each unit equivalent to 2,250,000 kva, three-phase, reclosing within 22 cycles for second tripping operation

18,300 amperes (see Table IV) corresponding to a three-phase fault of 4,200,000 kva at 132 kv, without the steel bolt toppling over.

Conclusion

As a result of extensive design and testing of high-voltage oil circuit breakers suitable for rapid reclosing duty cycles, the following general conclusions may be drawn:

1. If the recently developed multiflow-deion-grid type of contacts is used, it appears practical to build high-voltage oil circuit breakers of maximum kilovolt-amperes with structural dimensions determined almost entirely by the electrical-insulation requirements.
2. Using a small auxiliary oil-flushing piston, a 230-kv breaker has been designed which is capable of interrupting line-charging current with a minimum of restriking.

3. The low arc energy of the multiflow interrupters makes them particularly suitable for high-capacity oil circuit breaker rated from 115 kv to 230 kv applied on rapid reclosing duty cycles.

Reference

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Reclosing of Single Tie Lines Between Systems

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THE urgent necessity for pooling reserve generating capacity has accentuated the importance of single tie-line interconnections equipped with high-speed reclosing breakers. In many cases faults on a single tie line between two systems can be cleared, and the line can be reclosed with the same reliability that would be obtained if two lines were used without high-speed reclosure. Where a single tie line is used to transmit power between two systems the line must be reclosed fast enough, following a fault, so that synchronism is maintained. Further, the resultant power surges and voltage dips should not cause excessive shock to the system. A brief review of system performance during a reclosing cycle is presented to outline the factors that are involved.

Many practical cases have been analyzed to determine the transient-stability limits for successful reclosure of single tie lines between steam-generating stations. These studies covered a wide range of generating capacities, amount of power transfer, various transmission voltages, and distances between systems. These data are shown in curve form which would be quite useful in determining the feasibility of reclosing and as a guide to the type of commercially available equipment best suited for a specific case.

System Performance During a Reclosing Cycle

In order to visualize readily what happens during a complete reclosing cycle, it is convenient to divide the sequence of operation in four steps, as follows:

1. The initial condition (steady state prior to fault).

2. The fault condition.

3. The fault-cleared condition (breaker open or de-energized period).

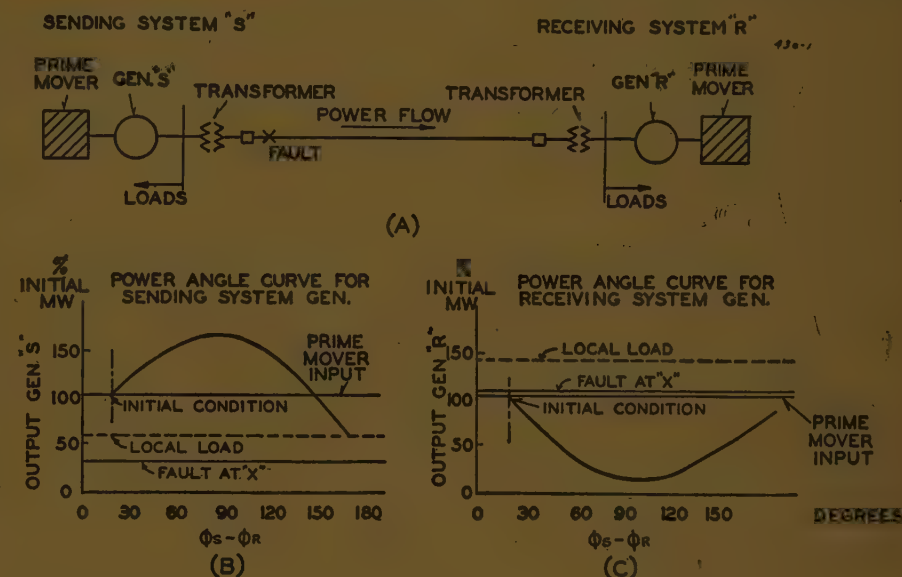
4. Condition after breakers are reclosed.

The sequence of events which take place during the reclosing cycle causes the electric outputs of the generators to differ from their respective prime-mover inputs. These changes result in swings of the rotors, the magnitudes of which are determined by the specific system and machine characteristics and the operating

power relations can be obtained either analytically or preferably by a-c network-calculator solution of the electrical networks involved.

Gain in System Performance With Single-Pole Switching

Consideration of single-pole switching presupposes that the transformer banks at both ends of the tie line are grounded solidly or through low values of impedance. The protective and reclosing relays are arranged to trip and reclose only those poles necessary to clear the fault. The unfaulted wire or wires and ground are available for transmitting power and maintaining voltage during the period when the faulted wire or wires are de-energized. Since the majority of faults do not involve all three wires, single-



ing conditions. Figures 1, 2, and 3 illustrate a typical case of successful reclosure following a fault on a single tie line. If reclosing had not been applied, in order to transmit firm power between the systems, two lines with a total of four breakers and control equipments would have been required. This example will be recognized as the familiar transient-stability problem in which the rotor positions and system voltage and current changes are obtained by well-known step-by-step stability calculations.^{1,2,3}

It is evident that, for any particular problem of tie-line reclosing involving a specific system, the factors affecting the transient-stability problem, and thus the choice of switching and control equipment, depend upon the electric-power output of the synchronous machines during the four periods in the reclosing cycle and the duration of these periods. The

Figure 1. Power-flow characteristics of two systems connected by a single tie line

A. System diagram

B. Power-angle curves of the sending system for normal three-phase fault and line-open conditions

ϕ_S = rotor phase angle of the sending-system generators

ϕ_R = rotor phase angle of the receiving-system generators

C. Same as B except for receiving system

pole switching in many cases will afford improved system performance.

Figure 4 shows a comparison of the phase-angle swings for three single-pole (individually operated) versus three-pole (gang-operated) breakers for various types of faults in a typical system. For a three-phase fault (Figure 4A) all three poles have to be opened to clear the fault so that there is no comparison between

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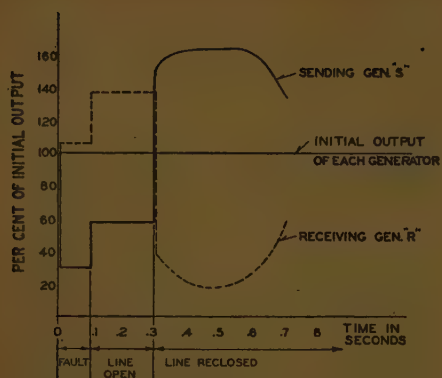


Figure 2. Electric-power output of generators for a typical reclosing cycle of the tie line of Figure 1

The fault near the sending end of the line is cleared in 0.1 second, and the line reclosed in 0.3 second

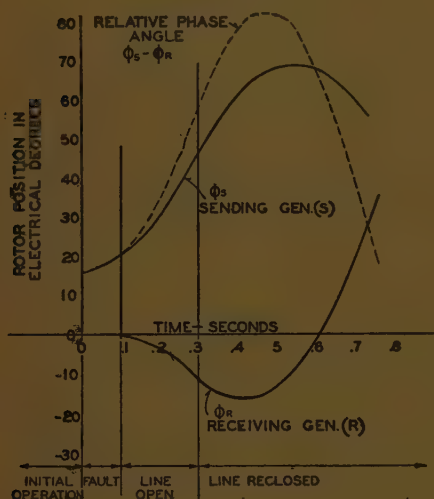


Figure 3. Rotor positions during the fault-clearing and reclosing cycle of the tie line of Figure 1

three single-pole or three-pole switching for this case. Figures 4B and 4C show considerable improvement in system operation with single-pole switching, as indicated by the smaller swings in phase angle of the generators.

Another measure of the severity of the disturbance to the system is the drop in voltage on the load busses. In general, the voltages decrease with the increase of the phase-angle difference between the two systems. For the case of Figure 4, the voltage at maximum swing at the receiver load bus in per cent of normal is shown in Table I.

Determination of the Type of Switching to Be Used for Specific Applications

The question to be decided in the determination of the proper choice of reclosing equipment is what type of commercially available reclosing breakers and control should be used when a desired amount of

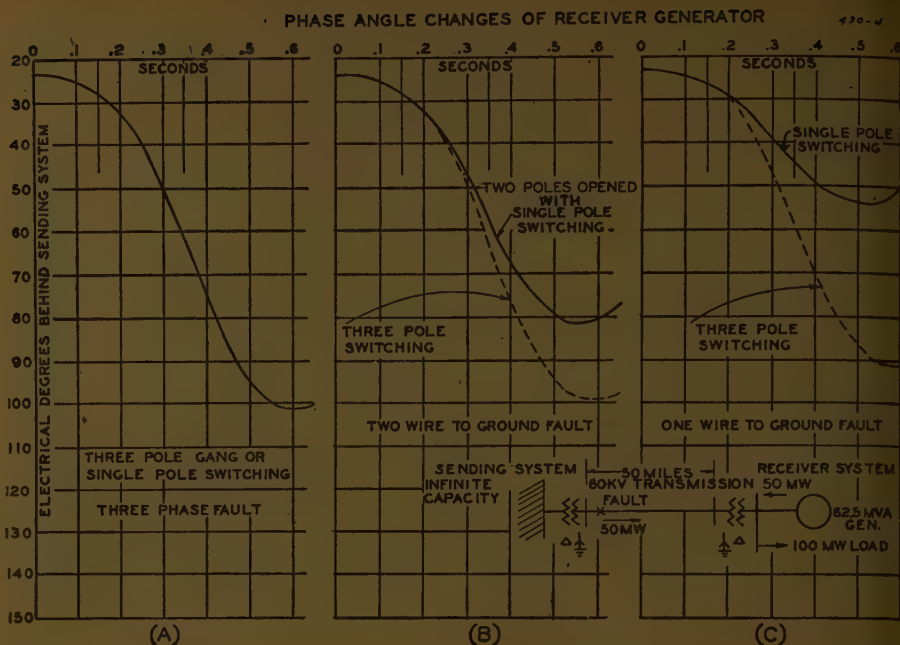


Figure 4. Comparison of system swings following fault, clearing of fault, and reclosing of a single tie line

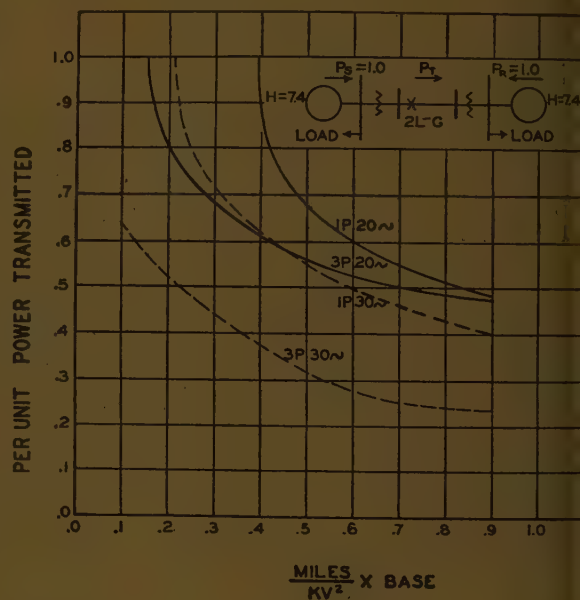
Fault cleared in nine cycles (0.15 second), and the line reclosed in a total time of 21 cycles (0.35 second)

Figure 5. Transient-stability limit for reclosing of a single tie line between two systems with equal steam-generating capacity connected

Base equals generating capacity in either system. Per unit power transmitted is referred to this base. Faults are double line to ground cleared in 0.15 second (nine cycles)

3P30~ = three-pole gang-operated breakers reclosed in 30 cycles. 3P20~ = three-pole gang-operated breakers reclosed in 20 cycles

1P30~ = individual pole-operated breakers reclosed in 30 cycles. 1P20~ = individual pole-operated breakers reclosed in 20 cycles



power is to be transmitted a given distance over a single line between two systems. Figures 5, 6, and 7 will be found directly useful in answering this question in a great many cases. These curves present the results of investigations of over 100 practical solutions. Each curve shows the transient-stability limits based on two line-to-ground faults for various ratios of power transmitted to size of the system plotted against a measure of the electrical length of the transmission line. There are four curves in each figure, one for each of four commercially available reclosing-breaker schemes. In addition on Figure 7 there is shown the curve for three-

pole 35-cycle reclosing. It is recognized that, at some of the higher-transmission voltages, this rather than 30 cycles is standard. The areas to the left and below these curves are regions below the transient-stability limit where successful reclosure would be obtained. The area to the right and above the curves are above the transient-stability limits for the respective types of reclosing equipment.

The use of these curves is illustrated in Table II where several typical examples are shown. The choice of which group of curves to use depends on the relative sizes of the sending and receiver system

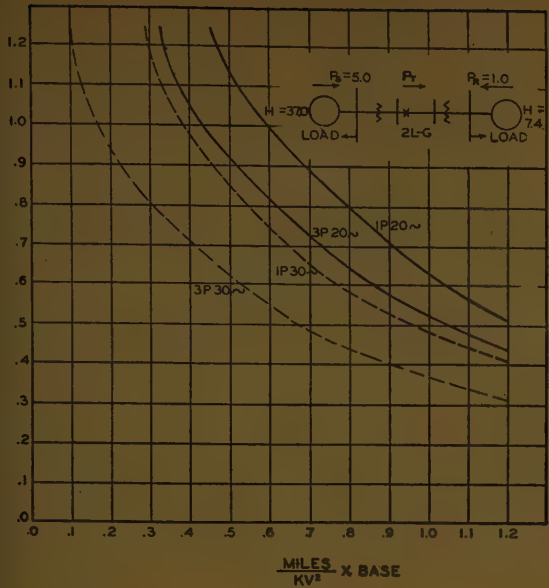


Figure 6. Transient-stability limit for reclosing of a single tie line between two systems with the steam-generating capacity of the sending system five times that of the receiving system

Base equals generating capacity in receiver system. Per unit power is referred to this base. Faults are double line to ground cleared in 0.15 second (nine cycles)

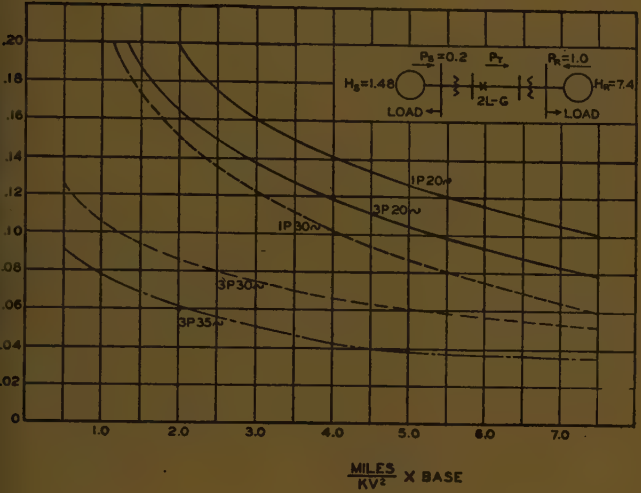


Figure 7. Transient-stability limit for reclosing of a single tie line between two systems with the steam-generating capacity of the receiving system five times that of the sending system

Base equals generator capacity in receiving system. Per unit power transmitted is referred to this base. Faults are double line to ground cleared in 0.15 second (nine cycles)

Table I

Type of Fault	Per Cent of Normal System Voltage	
	Three-Pole Switching	Single-Pole Switching
Three phase.....	73.5	73.5 (all 3 poles open)
Two lines to ground....	74.5	82 (2 poles open)
One line to ground....	78.0	93 (1 pole open)

Figure 5 is used if they are equal substantially. Figure 6 is used if the sending-end connected capacity is in the order of five times that of the receiver. Figure 7 is used if the receiver system has five times the capacity of the sending system. For other relative sizes interpolation is possible.

The data plotted on Figures 5, 6, and 7 were obtained from transient-stability solutions of examples with constants and initial operating conditions so chosen that the results applied to a large range of systems. The initial operating conditions for each point on the curves were obtained by establishing voltage and power flows that could be expected reasonably under practical operating conditions. The base selected was equal to the kilowatt capacity of the receiver system. The total amount of generation in either system was assumed to be made up of the necessary number of 1,800-rpm 80 per cent power-factor machines operating at full kilowatt load and excitation as required. The constants of the machines used were $H=7.4$, $x_d'=0.23$, $x_2=0.15$, $r_1=0.900$, and $r_2=0.035$. The shunt loads were assumed to be at 85 per cent power

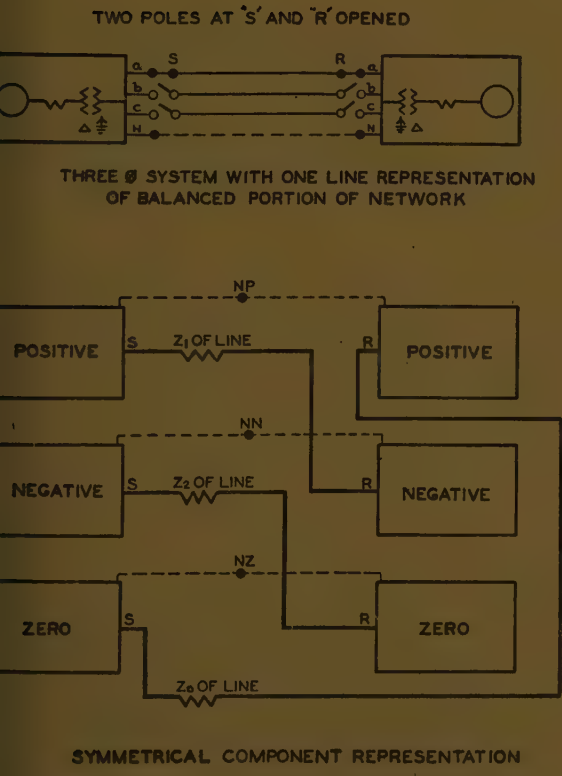
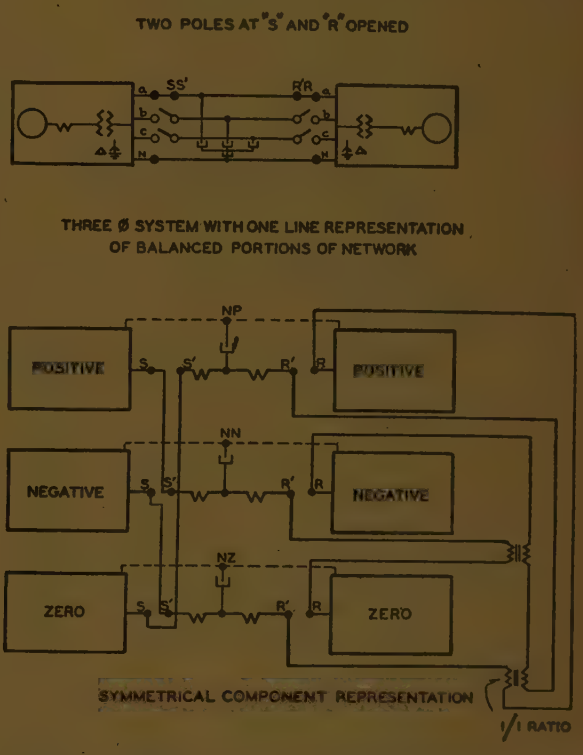


Figure 8. Electrical representation of condition following the clearing of a fault on a single tie line

A (left). Two-line-to-ground fault on a short line (negligible charging capacity)



B (right). Two-line-to-ground fault on a long line (charging capacity included)

Table II. Examples of Use of Figures 5, 6, and 7 to Determine Suitable Switching for Specific Cases

PS=Generation at Sending End (Megawatts)
 PR=Generation at Receiving End (Megawatts)
 PT=Maximum Power to Be Transmitted (Megawatts)

Case Number	Known System Characteristics					Per Unit PT	Miles	$\frac{\text{Miles}}{\text{Kv}^2} \times \text{Base}$	PS/PR	Use Figure	Synchronism* Maintained With Following Types of Reclosing
	PS	PR	PT	Kilo-volts	Miles						
1.....	50.....	50.....	25.....	69.....	40.....	0.5.....	0.42.....	1.....	5.....	{ 1 pole, 30 cycle 3 pole, 20 cycle 1 pole, 20 cycle None	
2.....	100.....	100.....	60.....	110.....	100.....	0.6.....	0.83.....	1.....	5.....		
3.....	250.....	50.....	25.....	69.....	40.....	0.5.....	0.42.....	5.....	6.....		
4.....	500.....	100.....	70.....	110.....	100.....	0.7.....	0.83.....	5.....	6.....	{ 1 pole, 20 cycle 1 pole, 30 cycle 3 pole, 20 cycle 1 pole, 20 cycle	
5.....	20.....	100.....	15.....	69.....	50.....	0.15.....	1.05.....	0.2.....	7.....		
6.....	100.....	500.....	70.....	110.....	90.....	0.14.....	3.72.....	0.2.....	7.....		

* When more than one type of reclosing is suitable so far as maintaining synchronism is concerned, the final choice will depend on other factors, such as the severity of the disturbance as measured by the voltage dips and power surges.

factor. The line regulation was adjusted to ten per cent. In certain cases this required that reactive kilovolt-amperes be furnished by the receiver system in excess of the capacity of the receiver generators. In these cases the additional reactive kilovolt-amperes required were assumed to be supplied by synchronous condensers. The inertia of these condensers was not included in the swing calculations as it usually was so small as to be negligible, and, even where condensers of considerable size were used, the omission of their inertia would tend to give pessimistic results.

Standard step-up and step-down transformers with per unit reactance of 0.085 were used. They were assumed to be connected delta-wye with the neutrals on the high side solidly grounded. The size of the transformers was equal to the power transmitted.

The line had the following characteristics:

- $x_1 = 0.71$ ohm per mile
- $y_1 = 5.8(10)^{-6}$ mhos per mile
- $r_0 = 0.45$ ohm per mile
- $x_0 = 2.84$ ohms per mile
- $r_1 = 0.35$ ohm per mile, or a value which would give 10 per cent loss in the line, whichever gave the smaller value of resistance

In using these line characteristics to obtain systems with practical operating conditions, it was assumed that the line would be operated at approximately unity power-factor loading. This means that the line charging kilovolt-amperes would be about equal to the i^2x consumed in the line.

The transient stability of the systems for the different distances and amounts of power transferred was calculated by obtaining the required power-angle diagrams from a-c network-calculator solution for:

1. The initial and reclosed conditions.
2. Two-wire-to-ground faults as the criterion for transient stability.
3. Two poles open for single-pole-opening breakers (see appendix).
4. Three poles open for gang-operated breakers.

When these power-angle diagrams were used, the usual step-by-step method of calculation was employed to determine the phase-angle swings of the machines for the various types of operation. By varying the length of line with all the other conditions held constant, the critical point was reached where an increase in distance would result in instability, and where shorter distances would prove stable.

Conclusion

The curves on Figures 5, 6, and 7 embody the results of such a multiplicity of practical system transient-stability solutions that they can be used as a guide in choosing the type of reclosing equipment for a single tie line between two steam-generating systems.

An inspection of these curves shows that single-pole switching in many cases offers a marked advantage over three-pole switching from the standpoint of transient stability based on two wire-to-ground faults. Further, additional advantages of single-pole switching accrue because the majority of faults (70 per cent or more) are single line to ground. If only one breaker pole is open, considerable synchronizing power is maintained during the clearing of this type of fault. This results in reduced voltage dips and system oscillations, as illustrated in Table I and Figure 4.

Appendix I

Figures 8A and 8B show the electrical connections of the three sequence networks to represent the unbalanced system conditions obtained by single-pole switching. It may be noted that, where there are shunt connections to the opened line as in Figure 8B, the multiple unbalances so produced are represented by using 1-to-1 ratio transformers in the connection of the networks. These connections have been developed from fundamentals previously described.

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Rectifier-Circuit Duty

C. C. HERSKIND

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THE usual rectifier unit consists of a transformer with a number of rectifying elements connected to its secondary windings. The rectifying action may be resolved into two parts, namely, the circuit action which is determined by the transformer and the a-c and d-c circuits, and the unidirectional switching action which is performed by the rectifying elements. The circuit action is defined by the number, arrangement, and constants of the circuits connecting the a-c and d-c systems. The switching action consists of connecting the various secondary windings of the transformer to the load circuit at selected intervals during each cycle by means of mercury-arc rectifiers, metallic rectifiers, vacuum tubes, and other types of rectifying elements.

The size and characteristics of the rectifying elements required for any rectifier unit depend upon the current each must carry during the conduction period and the voltage it must withstand during the idle period. Although the rectifying element may control the time at which conduction starts (as, for example, in phase-controlled rectifiers), in other respects it is a passive element, since the voltage and current impressed upon it are determined by the circuit constants. The nature and value of the voltage and current appearing on the rectifying elements, that is, the loading on these elements, may be termed the circuit duty. Conversely, the capability of the rectifying element may be termed the rectifier capacity. The rectifier capacity may be measured in terms of the maximum circuit duty at which it is capable of operating without failure.

These terms may be defined as follows:

The rectifier-circuit duty is the voltage and current loading applied to the rectifying element by the rectifier circuit.

The rectifier capacity is the maximum loading at which the rectifying element is capable of operating without failure. It may be expressed in the same terms as the circuit duty.

The concept of rectifier-circuit duty and rectifier capacity provides a con-

venient and useful means for analyzing the action taking place in any rectifier equipment. It permits a division of engineering functions into two parts, one of which deals with the analysis and application of rectifier circuits, whereas the other is concerned with the design and construction of suitable rectifying elements. Such a division of the engineering functions involved in rectifier design is not new but has been employed for some time in the design of small vacuum-tube rectifiers, where the performance of the tube is specified by itself, and the same tube may be used in a wide variety of applications. The effect of circuit upon performance is recognized also in the design and application of metallic rectifiers.

The application of this method of analyzing rectifier action requires a knowledge of the factors which limit the rating of the rectifying elements. Since arc-back behavior is a primary consideration in the performance and rating of mercury-arc rectifiers, and the functional relations between circuit factors and arc-back have not been established fully, this method has heretofore been used only in a very general way. However, a better understanding of the factors which limit rectifier rating is obtained if the circuit duty is determined on the basis of relations between the impressed voltage and current and the occurrence of arc-back, as indicated by studies of the physical action taking place within the rectifier.

It is the object of this paper to present an analysis of rectifier circuits in terms of circuit duty and rectifier capacity, discuss the various factors involved, and compare the various types of rectifier circuits.

Elements of Circuit Duty

It appears axiomatic that the duty on the rectifying elements arises from both the magnitude and the shape of the voltage and current waves, the effect of wave form depending upon the type of rectifying element employed.

Typical voltage and current waves on the rectifying element in a rectifier circuit are shown in Figure 1. A study of the physical processes which take place in the rectifying elements indicates that the circuit duty may be expressed in

terms of the following voltages and currents:

Voltage

1. Peak inverse voltage.
2. Rms inverse voltage.
3. Initial inverse voltage.
4. Peak forward voltage.

Current

5. Average current.
6. Peak current.
7. Rms current.
8. Final commutation rate.

PEAK INVERSE VOLTAGE

The peak inverse voltage is a measure of the maximum dielectric stress applied across the rectifying element during the idle period. Failure from excess voltage may take various forms, such as flashover, puncture of dielectric materials, or excessive glow discharge resulting in arc-back.

RMS INVERSE VOLTAGE

The rms value of the inverse voltage appears to be important only in the case of rectifiers having appreciable leakage current during the inverse period, where it provides a measure of the heating resulting from this leakage current. The leakage resistance characteristics of metallic rectifiers (such as the copper-oxide and selenium types) are nonlinear, and an accurate determination of the losses may require weighting factors other than those given by rms values. However, the heating due to the leakage current is usually given in terms of the rms values of the inverse voltage because of the ease with which such values may be determined.

INITIAL INVERSE VOLTAGE

The ionization in a mercury-arc rectifier does not disappear immediately upon the extinction of anode current, and, therefore, some residual ionization is present during the idle period. The amount of the residual ionization is greatest at the beginning of the idle period and decays as a function of time. The action of the

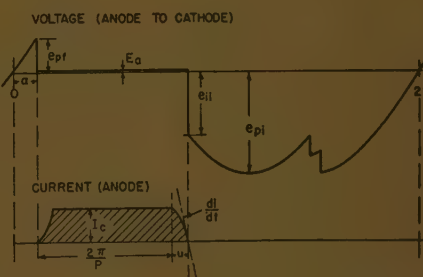


Figure 1. Typical voltage and current waves on rectifying element

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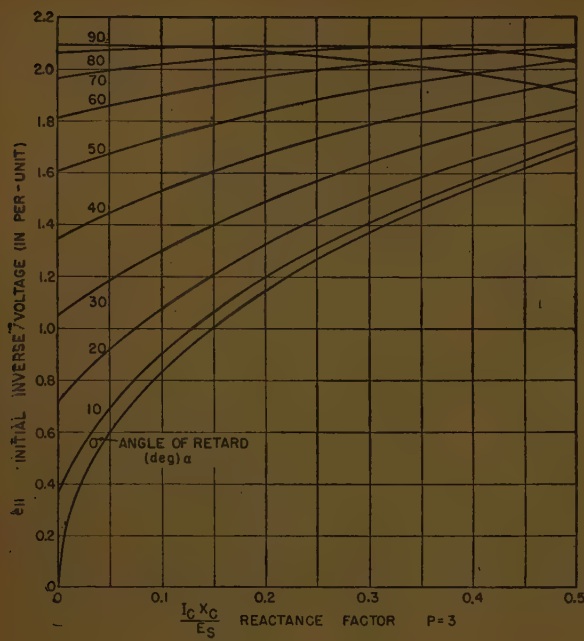


Figure 2. Initial inverse volt-

$P=3$

Per unit base is E_{do}

$$\frac{e_{ii}}{E_{do}} = \frac{2\pi}{P} \sin(u + \alpha)$$

rectifier circuit results in a sudden application of negative voltage across the rectifying element immediately following conduction. This negative voltage acting upon the residual ionization attracts positive ions to the anode. Since the positive ion bombardment may cause arc-back, the initial inverse voltage is a factor in the duty applied to a mercury-arc rectifier.

PEAK FORWARD VOLTAGE

When a rectifier is operated with the d-c voltage reduced by phase control, a positive voltage is applied across the rectifying element during the latter part of the idle period. This forward voltage imposes a further requirement upon the control characteristics of the rectifying element, since conduction must not occur before the desired firing time.

AVERAGE CURRENT

The average current passed by the rectifying element is a convenient measure of the duty imposed upon it, since this value bears a simple relation to the load current on the rectifier unit. For this reason the current capacity of the rectifying element is customarily expressed in terms of average current. However, the average current does not bear so definite a relationship to the physical action and physical limitations of the rectifying element as do the peak and rms current values.

PEAK CURRENT

The losses resulting from the passage of current are one of the factors which limit the capacity of the rectifying elements. However, the nature of the current limitations in mercury-arc rectifiers is somewhat different from that in other electric apparatus, since failure by arc-back may occur without measurable temperature

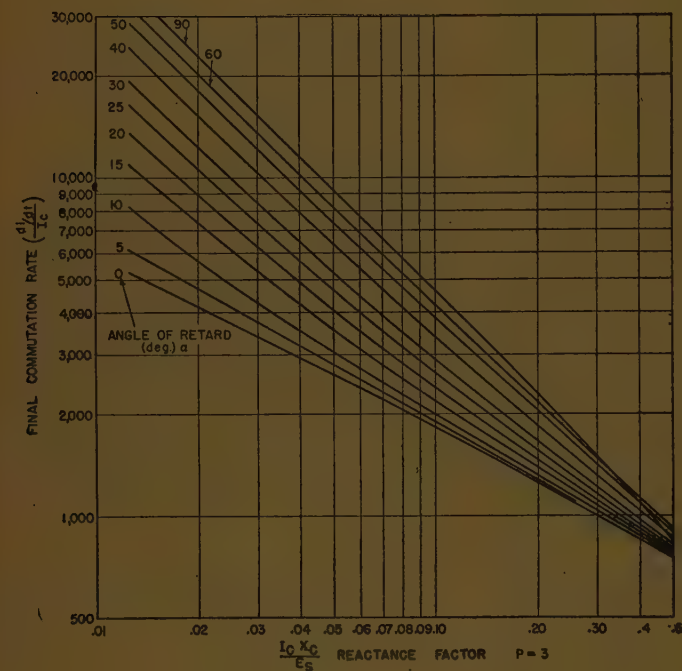


Figure 3. Final commutation rate $P=3$, $f=60$ cycles

Multiply values of $\frac{di}{dt}/I_c$ given on curve by direct current commutated I_c to obtain commutation rate in amperes per second

$$\frac{di}{dt} = \left[\frac{\omega P}{\sqrt{2} \pi} \sin \frac{\pi}{P} \right] \cdot \frac{E_s}{X_c} \frac{e_{ii}}{E_{do}}$$

Figure 4. Comparison of circuit duty of simple rectifiers

NO. OF PHASES	1	3	4	6	12
NAME	SINGLE PHASE	THREE PHASE	QUARTER PHASE	SIX PHASE	TWELVE PHASE
CIRCUIT DIAGRAM					
WAVE FORMS					
CIRCUIT DUTY					
DC VOLTAGE $E_{do}/E_s = 0.45$	0.90	1.17	1.27	1.35	1.41
PEAK INVERSE $e_{pi}/E_{do} = 3.14$ VOLTAGE	3.14	2.09	2.22	2.09	2.02
AVG. ANODE CURRENT = 1.00	0.50	0.33	0.25	0.167	0.083
RMS ANODE CURRENT = 1.57	0.707	0.577	0.50	0.408	0.288
PEAK ANODE CURRENT = 3.14	1.00	1.00	1.00	1.00	1.00

* (IN PER-UNIT ON BASE OF LOAD CURRENT I_d)

ise. As the instantaneous arc drop is a function of the instantaneous current, the peak anode current is an important factor in the determination of the loading. Furthermore, the conditions existing in the mercury vapor at the end of the conducting period are a function of the peak current which has passed during conduction, and the peak current, therefore, influences the probability of arc-back. In the case of heated cathode rectifiers, the output of the rectifier is limited by the maximum emission which may be obtained from the cathode without damage.

RMS CURRENT

The heating in the leads and other conducting parts of the rectifying element depends upon the rms value of the current.

FINAL COMMUTATION RATE

The amount of residual ionization present at the beginning of the inverse period depends in large measure upon the rate of reduction of current during the last few degrees of conduction. The final commutation rate is the rate of change of anode current at the instant of extinction and in some cases may be taken as a measure of the amount of residual ionization present in the rectifier at the time that the initial inverse voltage appears across it. Therefore, the final commutation rate is a further element in the duty on the rectifier.

The commutation rate also may be of importance during the initial part of the conduction period when the rate of current build-up exceeds the ionization rate of the rectifier. Under such conditions additional local heating and voltage stresses may be imposed upon the rectifier.

The researches of Kingdon and Lawton¹ have shown that there is a definite relation between the residual ionization and the arc-back frequency. Under certain conditions the frequency of arc-back due to residual ionization is a function of the product of the initial inverse voltage by the final commutation rate. Since arc-backs in mercury-arc rectifiers are caused by many factors, this relationship has not been established fully on commercial rectifiers. However, experience with many rectifier installations indicates that some such relationship does exist.

Determination of Circuit Duty (Circuit Analysis)

The circuit duty may be determined by an analysis of the action in a simple rectifier circuit. The formulas for the

NO. OF PHASES IN EACH SIMPLE RECTIFIER P		NO. OF IN EQUIV. SIMPLE RECTIFIERS Q		NO. OF SIMPLE RECTIFIERS R		CIRCUIT DIAGRAM
2.		4		2		
(DOUBLE - BIPHASE)						
2		6		3		
(TRIPLE - BIPHASE)						
3		6		2		
(DOUBLE - WYE)						
3		12		4		
(QUADRUPLE - ZIG-ZAG)						
6		12		2		
(DOUBLE - SIX PHASE)						

Figure 5. Multiple rectifiers

various elements of circuit duty for a simple rectifier of P phases follow.

The peak inverse voltage (e_{pi}) expressed in terms of the theoretical d-c voltage E_{do} is

$$e_{pi} = K \frac{\pi}{P \sin \frac{\pi}{P}} E_{do} \quad (1)$$

where

K = ratio of secondary voltage across phases to secondary voltage line to neutral
(When $P=3$ the value of K is $\sqrt{3}$, and when $P=2, 4, 6$, and 12 the value of K is 2)

The rms inverse voltage is not given here but may be determined from the inverse-voltage wave by integration.

The initial inverse voltage (e_{ii}) is given by the expression

$$e_{ii} = \frac{2\pi}{P} E_{do} \sin(u + \alpha) \quad (2)$$

where

u = angle of overlap and
 α = angle of phase retard

The initial inverse voltage for a simple three-phase rectifier is shown in Figure 2.

The peak forward voltage (e_{pf}) is

$$e_{pf} = \frac{2\pi}{P} E_{do} \sin \alpha \quad (3)$$

The average and rms current passing through the rectifier elements may be

expressed in terms of the direct current commutated I_c (peak current) as follows:

$$\text{average current} = \frac{I_c}{P} \quad (4)$$

$$\text{rms current} = \frac{I_c}{\sqrt{P}} \quad (5)$$

The final commutation rate (di/dt) may be obtained by differentiating the expression for the commutating current. The resulting value is

$$\frac{di}{dt} = \left[\sqrt{2} \omega \sin \frac{\pi}{P} \right] \cdot \frac{E_s}{X_c} \cdot \sin(u + \alpha) \quad (6)$$

$$= \left[\frac{\omega}{\sqrt{2}} \frac{P}{\pi} \sin \frac{\pi}{P} \right] \cdot \frac{E_s}{X_c} \cdot \frac{e_{ii}}{E_{do}} \quad (7)$$

where

$\omega = 2\pi f$, f = frequency of supply system
 X_c = commutating reactance, ohms line to neutral
 E_s = secondary voltage to neutral in rms volts

The variation in final commutation rate with the reactance factor is shown in Figure 3.

The analysis of any of the more complex rectifier circuits is facilitated by breaking them down into their component simple rectifiers. In cases where the rectifier installation has many phases which are displaced so as to obtain an equivalent simple rectifier with many phases, commutations will overlap, and the determination of the initial inverse voltage and final commutation rate becomes more difficult. Although it is possible to analyze such circuits, in general, it may be more practical to determine these elements of circuit duty by direct measurement.

Circuit Constants Versus Circuit Duty

Rectifier specifications covering rating and operating characteristics usually include the following factors:

1. Connection diagram (number of phases of equivalent simple rectifier).
2. D-c voltage.
3. Load current.
4. Voltage regulation (reactance of transformer and a-c system).
5. Amount of phase control.

The preceding factors, while they are very useful in the description of the complete equipment, do not provide much information with regard to the choice of rectifying elements. However, these factors bear a functional relationship to the elements of circuit duty and serve

NO. OF PHASES IN EACH SIMPLE RECTIFIER P	NO. OF IN EQUIV. SIMPLE RECTIFIER Q	NO. OF SIMPLE RECTIFIERS R	CIRCUIT DIAGRAMS
3	6	4	 (QUADRUPLE - WYE)
6	6	2	 (DOUBLE-SIX PHASE)

Figure 6. Parallel rectifiers

as a basis for the determination of the circuit duty imposed on the rectifying elements. The relationship between these factors and circuit duty is shown by the following examples:

SIMPLE RECTIFIERS

The wave form of the voltage and current on the rectifying elements for various simple rectifiers is shown in Figure 4. The circuit duty for each of these connections may be calculated by the foregoing formulas.

MULTIPLE RECTIFIERS

Most rectifier installations use a combination of simple rectifiers in multiple, parallel, cascade, or series in order to obtain the most economical arrangement and the desired operating characteristics. Such circuits may be broken down into component simple rectifiers and circuit duty determined from the foregoing formulas. A number of commonly used multiple rectifier circuits is shown in Figure 5 and two parallel rectifier circuits in Figure 6.

DOUBLE-WAY RECTIFIERS

Double-way circuits may be reduced to the form of simple rectifiers in cascade or series. Figure 7 shows two frequently used double-way rectifier circuits with the equivalent cascade or series circuits.

COMPARISON OF THREE SIX-PHASE CIRCUITS

A comparison of the circuit duty incurred in three different six-phase rectifier circuits having the same rating and the same regulation characteristics is shown in Figure 8. The values given in this comparison are based on a six-anode rectifier rated 1,500 kw at 600 volts and 2,500 amperes. The theoretical voltage for each of the three cases is $E_{d0}=650$, and the voltage regulation due to trans-

Figure 7. Double-way rectifiers

NO. OF PHASES IN EACH SIMPLE RECTIFIER P	NO. OF IN EQUIV. SIMPLE RECTIFIER Q	NO. OF SIMPLE RECTIFIERS R	CIRCUIT DIAGRAMS	EQUIVALENT SEC. CIRCUIT
2	2	2		
3	6	2		

former reactance is assumed to be $E_x/E_{d0}=0.035$. With the usual transformer resistance such a rectifier would have a normal regulation of approximately five per cent. It is assumed that the rectifier is operated with no phase retard.

EFFECT OF REACTANCE

The effect of reactance upon the initial inverse voltage and final commutation rate is shown in Figure 9. With reference to this figure, the solid curves are the same as those for the delta double-wye rectifier circuit in Figure 8 and for a rectifier having a voltage regulation $E_x/E_{d0}=0.035$. The dotted curves give the values for a rectifier having twice the transformer reactance and, therefore, twice the value of regulation. The effect of increased reactance is to increase the initial inverse voltage and to reduce the commutation rate.

EFFECT OF PHASE CONTROL

The effect of phase control upon the initial inverse voltage and final commutation rate is shown in Figures 2 and 3. The application of phase control increases both the initial inverse voltage and the final commutation rate. Experience shows that the probability of arc-back is increased when a rectifier is operated with phase control.

Selection of Rectifier Circuits

The choice of the rectifier circuit for any specific application is based on considerations involving wave form, power factor, regulation, and efficiency requirements. The rating and characteristics of the rectifying elements available must be considered also.

WAVE FORM

The number of phases of the rectifier circuit is selected so as to obtain a suitable wave form. Most rectifier equipments in the higher ratings consist of a

number of rectifier units displaced in phase so as to reduce the magnitude of the harmonics in the a-c and d-c systems. The minimum number of phases is usually six, and the number increases to 12, 24, 36, and so forth for the larger installations.

REGULATION

The inherent regulation of the rectifier is determined primarily by the reactance of the rectifier transformer. The value of reactance is chosen so as to obtain the desired regulation characteristic.

Another important consideration in the selection of transformer circuit reactance is the magnitude of fault current under d-c short circuit and arc-back. The fault current is a primary factor in the circuit duty under short-circuit conditions, and the circuit reactance must limit the current to a value less than the fault-current capacity of the rectifying elements.

The effect of type of circuit upon the transformer reactance and d-c short-circuit current is shown in the comparison of three six-phase circuits in Figure 8.

In 12-phase circuits the transformer reactance and the d-c short-circuit current depend upon the arrangement of the transformer windings. For example, by interlacing the secondary windings of the quadruple zigzag transformer shown in Figure 10b, the values of transformer reactance will be twice and of d-c short-circuit current half those obtained on the quadruple-wye transformer shown in Figure 10a for the same voltage regulation.

One advantage of the double-way circuit shown in Figure 7 is that there is no d-c feedback during arc-back, since this circuit is equivalent to two simple rectifiers in series.

EFFICIENCY

Best utilization of transformer windings is obtained usually with a circuit consisting of a number of simple three-

Figure 8. Comparison of three six-phase circuits for rectifier rated 600 volts, 1,500 kw

phase rectifiers arranged in multiple and parallel combinations, and, for this reason most rectifier installations employ this type of circuit. These circuits also result in a good utilization on the rectifier. ■

A six-phase fork connection is used

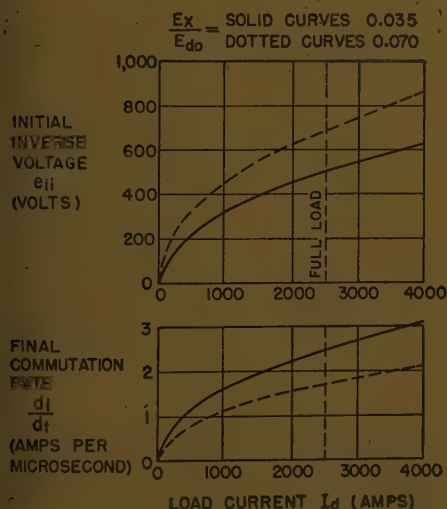


Figure 9. Effect of reactance on initial inverse voltage and final commutation rate

often on certain sizes of rectifiers. Some of its advantages are elimination of the interphase transformer, simplification of the control circuit, and elimination of the possibility of transformer unbalance. However, with this circuit, the peak anode current has twice the value obtained in a double-wye circuit, and the rectifier capacity is reduced, while the arc losses are increased. Tests on six-anode ignitron rectifiers show that the full-load arc losses are approximately 8 per cent greater when operating fork-connected than when operating double-wye.

Special Circuits

A number of circuits providing a variety of operating characteristics and different modes of operation is shown in Figure 11.

The first of these is a single-phase rectifier circuit having three different modes of operation. In this circuit the mode of operation is determined by the constants of the d-c load. The voltage and current wave forms for the different cases are shown.²

The second circuit is a simple biphasé

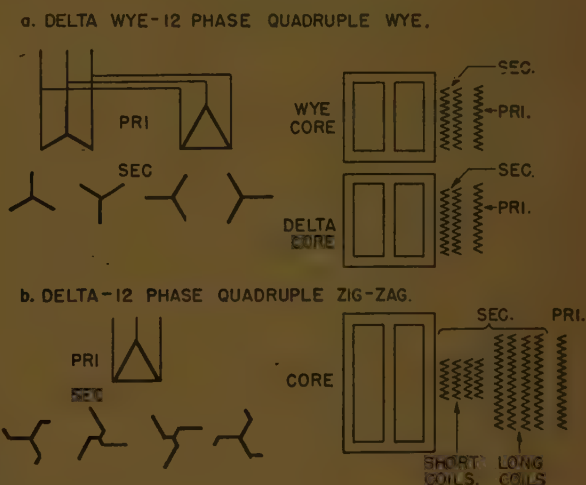


Figure 10. Quadruple-wye and quadruple-zigzag circuits

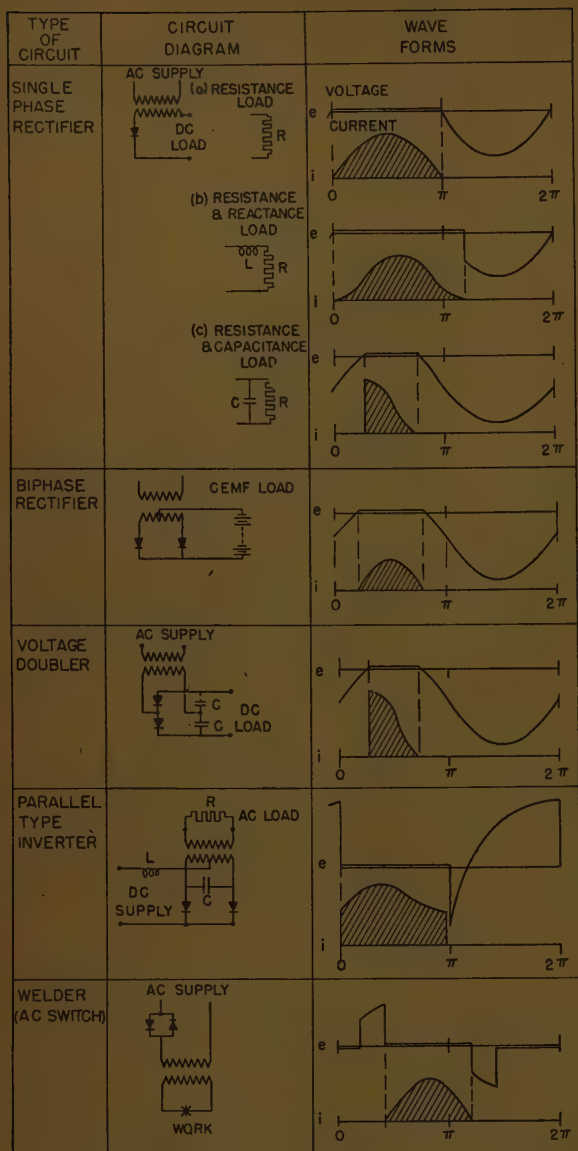


Figure 11. Special circuits

Conclusion

The diversity of rectifier applications has increased rapidly during the past few years, so that today there are available, in addition to the rectifier, a large number of power electronic devices, such as rectifiers with voltage control, inverters, frequency changers, welders, and electronic switches. With such a wide variety of rectifier applications the problem of matching the performance of the circuit with that of the rectifying element assumes greater importance.

Several advantages are obtained by expressing the rectifying action in terms of circuit duty and rectifier capacity, namely:

1. A division of engineering functions is made possible. The analysis, calculation, and selection of rectifier circuits and rectifying elements for different applications is one project while the design, testing, and rating of rectifying elements is the other; and the two may be carried out independently.
2. The elements which must be considered in determining the capacity of all types of rectifying elements are defined.
3. The method for determining the limitations of the rectifying elements is indicated.
4. A common basis for the rating of all types of rectifying elements is provided.
5. The application of any rectifying element to a wide variety of circuits is facilitated.

It is hoped that this method of analysis may be extended to all types of circuits using rectifiers, and that a standard basis for rating all types of rectifying elements may be developed.

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rectifier operating with a counter electromotive-force load.³ In the usual mode of operation for this circuit the load current is intermittent. The range of intermittent operation depends on the circuit constants and the amount of phase control.

The third circuit shows a voltage doubler.⁴ This is a double-way circuit, and the voltage and current waves across the rectifying element are similar to those for the single-phase rectifier with resistance and capacitance load.

The fourth circuit shows a parallel-type inverter.⁵ The voltage and waves of the parallel-type inverter differ from those for most rectifiers in one important respect, namely, the voltage across the

rectifying element is negative for only a short part of the inverse period immediately following conduction. During the remainder of the conduction period a positive voltage is applied across the rectifying element. This type of voltage wave is common to most inverter circuits and imposes a duty which differs from that of the usual rectifier.

The fifth circuit shows a welder or a-c switch.⁶ This type of circuit employs two rectifying elements connected so as to permit current flow in opposite directions, and the combination operates as an a-c switch. It has found widespread application in resistance welding.

The foregoing examples are only a few of a large variety of new applications.

A Versatile Power-Line-Carrier System

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POWER-LINE carrier has kept pace with the swift progress of the electronic art during the last several years. This progress has been due mainly to the stimulus injected by the war effort. In most of the specialized fields of electronics, the advancement was necessitated and promoted strictly for military purposes. Power-line carrier, however, was and is the soldier of the home front. Its duties have been expanded to include as many functions as possible consistent with reliability, economy, and convenience. The economic feature is especially significant now, since, during wartime emergencies, the material resources of the nation are allotted, and properly so, to those agencies concerned with the battle front. Material for new power lines, new generating equipment, new telephone lines, and for other similar programs of expansion is therefore not generally available. However, power-line carrier comes to the rescue and effectively provides additional circuits and higher power-handling capacity for existing installations.

Functions of Power-Line Carrier

For over two decades carrier frequencies have been used on power transmission lines to provide a channel between generating plants, substations, and similar terminals for communication, and, more recently, for high-speed relaying. However, with the development and expansion of large interconnected power systems, the available carrier channel has been used for a number of other functions. In fact, the additional services provided by a carrier system often have been the deciding factor in justifying its installation. A typical list of functions would include the following:

1. Carrier relaying (and emergency communication).
2. Telemetry and load control.
3. Supervisory control.
4. Remote or transferred tripping.
5. Communication.

It is the purpose of this paper to show how a carrier channel can be utilized to provide these additional functions by means of audio tone modulation of the carrier signal.

Advantages of Tone Modulation

A power-line-carrier installation employing unmodulated carrier can be used for only one function at a time, such as relaying, telemetry, or communication. By modulating the carrier with audio tones and separating the tones at the receiving end of the circuit with suitable filters, it is possible to maintain two or more functions simultaneously over a single carrier channel. There are several advantages of such a system: the effective selectivity of the receiver is increased, permitting more functions in one channel, and the effect of noise on the transmission line is reduced.

Figure 1 shows how the effective selectivity of the receiver is increased. If no tones were used, just one function could be transmitted over the carrier channel. On the basis of a total band width of only 1,650 cycles, the received side frequency furthest removed from the carrier would be 825 cycles. If tones are to be received, but no voice communication, it would be practical to use frequencies of 150, 209, 290, 403, 560, and 778 cycles per second, which amounts to 38 per cent separation between tones. With such a separation, audio filters of sufficient selectivity to pass one tone and reject all others can be designed readily. If one tone per function is allowed, this provides for six functions in a single carrier channel where only one was available without tones. Thus the effective selectivity of the receiver has been increased six times.

In addition, it is better to obtain extreme selectivity with audio filters rather than with highly selective carrier-frequency circuits. When the figures in the preceding paragraph are used with six-tone pass bands and six corresponding no-pass bands between zero and 825 cycles, a 778-cycle tone filter can have a pass band approximately 90 cycles wide. Then the 778-cycle oscillator may have a drift of ± 45 cycles or $\pm$ six per cent and

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still remain within the filter pass band. However, to maintain the same effective selectivity with carrier-frequency circuits, the frequency drift could not exceed ± 0.045 per cent (± 45 cycles at 100 kilocycles). Therefore, the stability of the carrier circuits need not be as great when tones are used as would be required to obtain the same effective selectivity with unmodulated carrier.

Noise on a power transmission line covers a wide frequency range, but the selective circuits of the receiver permit the reception of only the noise components in the channel to which it is tuned. When no tones are used, it is advantageous to adjust the receiver to accept only a narrow band of frequencies, as the line

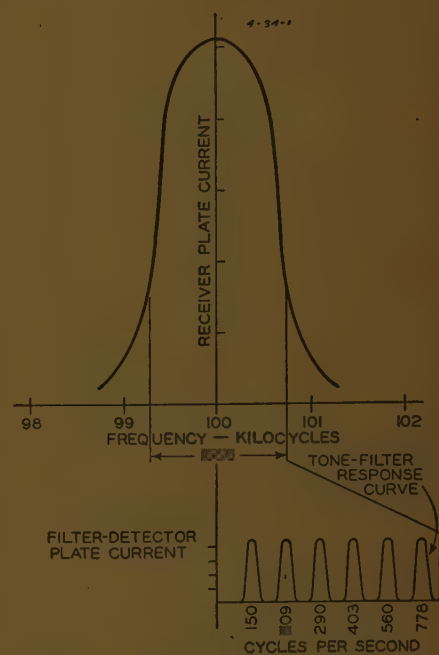


Figure 1. Typical receiver and tone-filter response curves

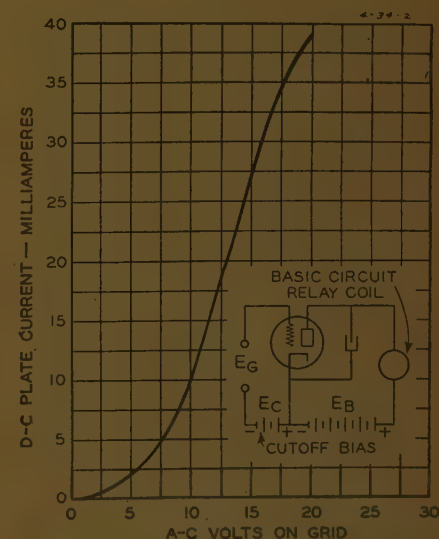


Figure 2. Dynamic characteristic of a biased detector

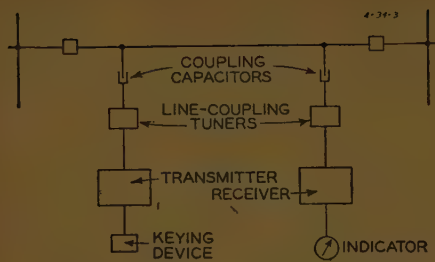


Figure 3. Simple carrier telemetering

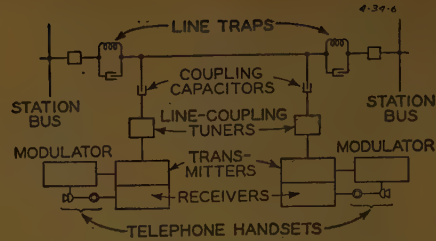


Figure 6. Carrier relaying plus modulator for communication

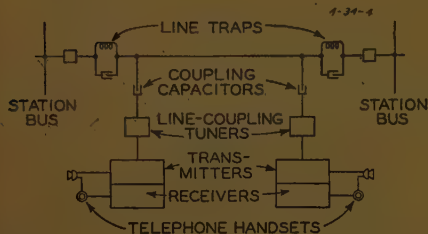


Figure 4. Basic carrier for pilot relaying

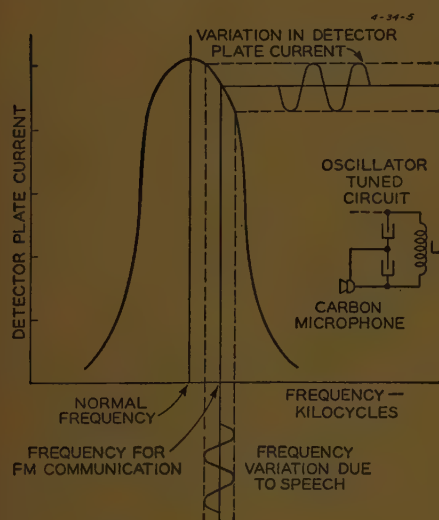


Figure 5. Method of receiving frequency modulation

noise received is proportional to the receiver band width. If the receiver output feeds six tone filters, then the noise accepted by each filter will be less than one sixth of the total noise received. How much less depends upon the filter selectivity. If the spacing between any two adjacent tone-filter pass bands is equal to the pass-band width in cycles, then the noise passed by each filter will be approximately one twelfth of the total noise received. Thus the use of tones reduces the effect of noise.

Further, if the filter feeds a biased detector, an additional advantage of three to one is obtained because of the non-linearity of the detector dynamic characteristic. A biased detector employs a vacuum tube operated with sufficient negative bias voltage on its control grid to cut off the flow of plate current when no signal is being received. When an a-c voltage is applied to the grid, plate

current flows on the positive half cycles. A plot of d-c plate current versus a-c grid voltage under operating conditions is known as the dynamic characteristic of the tube circuit. A typical curve is given in Figure 2. Reference to the curve shows that if a noise level of five volts is applied to the detector grid, the tube plate current is two milliamperes; if the noise plus signal is ten volts, the plate current is ten milliamperes. A relay adjusted to operate at six or eight milliamperes will not be operated by a noise voltage of five volts, yet reliable operation will be obtained on a total noise plus signal voltage of ten. This is a major advantage of tone-modulated carrier as it allows satisfactory reception of a signal through noise of approximately the same magnitude.

Expansion of a Carrier System

The following paragraphs trace the expansion of a power-line-carrier system from the simplest single-purpose arrangement to a complex installation which will provide several functions simultaneously in addition to carrier relaying. Figure 3 shows the simplest arrangement which will provide for telemetering a single quantity over a carrier channel. At the sending end, a transmitter is coupled through a line-tuning unit and coupling capacitor to the power line. In one system, the transmitter is turned on and off, or "keyed," by the telemetering device at a rate governed by the quantity being measured. In another system, the impulse rate remains constant, but the duration of the impulse varies. The carrier-frequency impulses so produced travel along the transmission line to the receiving end which employs similar coupling and tuning equipment, and, in addition, a receiver tuned to the transmitted frequency. The received impulses indirectly energize an indicating or recording instrument, giving a reading proportional to the quantity being measured at the transmitting end.

Line traps are generally unnecessary when carrier relaying is not included but

may be used if the line loss between stations and the number of paths over which the carrier energy can divide are too great. Traps may also be used if different conditions of line switching cause wide variations in carrier loss between stations. However, this will not always eliminate signal variation as an appreciable fraction of the total carrier energy can flow in the untrapped phases of the transmission line. This energy goes on into other line sections and may cause increased loss because of reflection or absorption. Three-phase trapping will eliminate such a condition, but the selection of a different carrier frequency usually obviates the necessity of inserting traps in all three phases. Energy absorbed by a parallel line is also a potential cause of increased loss, but this, too, can be minimized by changing the frequency.

Figure 4 illustrates the basic carrier elements required for pilot relaying. The carrier signal for relaying is used to prevent the protective relays from tripping the breakers in a given line section for a fault external to that section. Carrier is transmitted from the station where fault power leaves the line section and blocks the relays at the station where the fault power enters the line section. Consequently, a transmitter, receiver, and suitable line-tuning and coupling equipment are located at each end of the line section to provide correct operation for external faults in either direction. Line traps are located between the coupling capacitor and the station bus in the phase wire to which carrier is coupled. From a relaying standpoint, the main function of a line trap is to prevent short-circuiting the carrier signal upon the occurrence of a ground fault just external to the line section on the phase wire to which carrier is coupled. Without the trap, such a fault might short-circuit the carrier signal and cause incorrect relay operation.

Supervisory control or telemetering of a single quantity in either direction can be provided in addition to relaying by keying the transmitter as before. The keying device for the added function is placed in parallel with the relay contacts which start carrier by closing the cathode circuit of the tubes in the transmitter. When high-rate telemetering is used, it is desirable to insert between the keying device and the carrier transmitter an electronic link which reduces to a fraction of a milliampere the current the telemetering contact is required to make and break in controlling carrier. Longer contact life and less maintenance

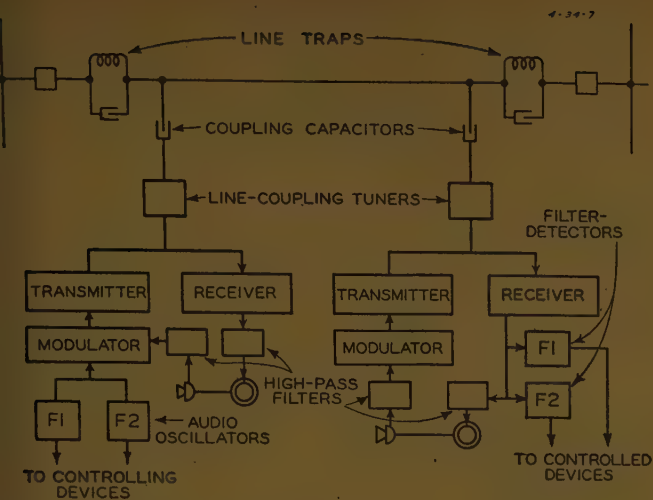


Figure 7. Audio tones added to carrier relaying

re the advantages of such an electronic link.

Emergency voice communication between the carrier equipments can be effected by connecting the handset microphone across a low impedance section of the oscillator tuned circuit. Variation in the microphone resistance due to speech results in frequency modulation of the transmitted carrier. To receive frequency modulation, the carrier receiver must be capable of producing an output voltage or current proportional to the instantaneous change in frequency of the transmitter. A normal relaying signal receiver can be used satisfactorily for this application for the following reasons: When the microphone is connected into the oscillator tuned circuit, the resonant frequency of the circuit is changed by a small percentage. The receiver, which is normally tuned exactly to the transmitter frequency, is now slightly off resonance, as indicated in Figure 5, and is operating on the sloping portion of its resonance curve. When the transmitted frequency shifts back and forth because of speech, the detector plate current varies accordingly, and an audible signal is produced in the handset receiver.

This is probably one of the oldest forms of modulation, but it is still applicable, as it provides intelligible communication with a minimum of additional parts.

If communication between stations is desired from the switchboard panel, a modulator may be added to amplitude-modulate the carrier signal. Figure 6 illustrates an assembly which provides for carrier relaying and "push-to-talk" voice communication over a line section. It can be used also for telemetering a single quantity. The systems dia-

grammed in Figures 4 and 6 can be used for only one function at a time. If telemetering is used, it must be suspended in order to talk over the carrier channel, and, of course, during a fault, the protective relays take precedence over all other functions in controlling carrier.

When it is desired to have several functions on a single carrier channel simultaneously audio tones can be used to advantage. For example, consider an installation of carrier relaying where voice communication and telemetering of two quantities are desired. In order to transmit two quantities without interference, the measuring device associated with each controls a separate audio tone oscillator which amplitude-modulates the carrier signal. At the receiving end, the modulated carrier is fed into a detector tube to separate the audio from the carrier. The audio is then fed into filter circuits, each of which is tuned to pass one of the tone frequencies. The output voltage of each filter is applied to the grid of a vacuum tube operated as a biased detector, the operation of which was previously explained. An auxiliary relay in the plate circuit of the "filter-detector" controls the telemetering indicating device. Figure 7 illustrates such a system which can be used for telemetering two quantities as explained heretofore, for load control, or for remote tripping. For load control, the two audio tones provide raise and lower impulses to the governor of a generator; for remote tripping, the contacts of the two filter-detector auxiliary relays are connected in series to energize the breaker trip coil. To initiate a remote-tripping operation, both audio tones are transmitted (started either manually or by protective relays), and both filter-detectors at the receiving end are energized, thus completing the breaker trip circuit. The purpose of using two tones in this manner is to reduce the possibility

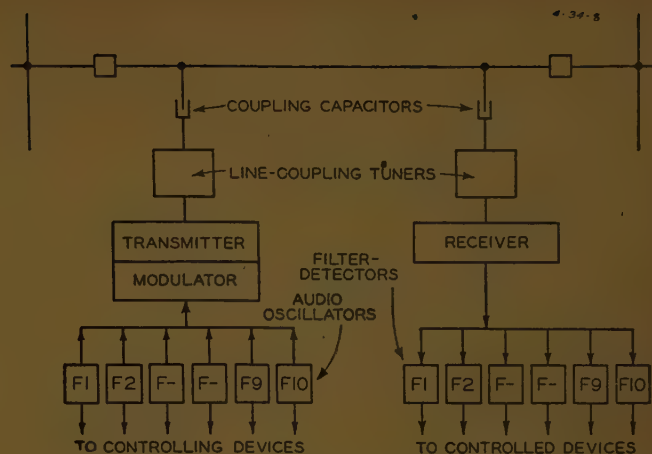


Figure 8. Use of tones to provide up to ten remotely controlled functions

of an incorrect breaker operation because of line noise or other disturbance producing a momentary signal which contains one of the tone frequencies.

If voice communication is included, a precaution must be taken to eliminate from the transmitter the voice frequencies which are identical with the tone frequencies. This is necessary to prevent speech from energizing the filter detectors at the receiving terminal and can be accomplished by inserting between the microphone and the modulator a filter which eliminates the tone frequencies from the speech input. By selecting tone frequencies below 500 cycles, several tones may be used simultaneously with communication. The speech filter can be of the high-pass type to attenuate all frequencies below 500 cycles 40 to 50 decibels so there is no danger of their energizing a filter detector. The elimination of these frequencies does very little to impair the intelligibility of speech.

In those cases where the tones are transmitted infrequently, as for remote tripping, the high-pass filters are not necessary in the telephone receiver circuit because the interference with speech reception is of short duration. However, for telemetering and other functions requiring the tones to be impulsed continuously, filters should be provided in the telephone receiver circuit. The aforementioned features are indicated in Figure 7.

Figure 8 illustrates extensive use of tones without communication or relaying and will provide up to ten remotely controlled functions over a single carrier channel. As all ten tones may be transmitted simultaneously, each tone must be adjusted to modulate the carrier signal not more than ten per cent to prevent overmodulation. This would cause severe distortion and generation of

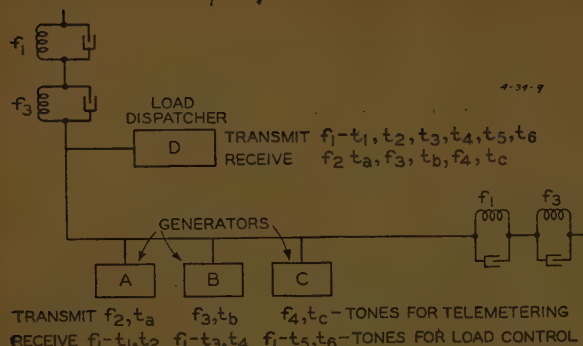


Figure 9. Extensive use of tones for telemetering and load control

$$f_2 = (N - 1.5) \text{ kilocycles}$$

$$f_3 = (N) \text{ kilocycles}$$

$$f_4 = (N + 1.5) \text{ kilocycles}$$

spurious side frequencies which are undesirable and may give interference in adjacent channels.

Since the percentage modulation per tone must be decreased when the number of tones is increased, the carrier side-band power in each tone is also decreased. Therefore, a more sensitive receiver is required for this application than for one where unmodulated carrier is received (assuming the same carrier power in both cases). Also, the receiver must have a low distortion characteristic so as to reproduce the tone frequencies without introducing unwanted harmonics. Ten audio tones can be spaced in a band from 150 to 3,000 cycles with a 38 per cent frequency separation between consecutive tones. To receive a carrier signal modulated with tones up to 3,000 cycles, the receiver must be capable of receiving a frequency band six kilocycles wide, and rejecting those outside the six-kilocycle band which may belong to another carrier channel. A simple receiver such as that used for relaying is not suitable for this application of tones. However, a broad-band superheterodyne receiver fulfills the preceding requirements of sensitivity, selectivity, and band width. Such a receiver should be equipped with automatic volume control to deliver sufficient audio voltage to the tone filters over a wide range of carrier input signal to allow for varying system conditions. For applications on lines with a high carrier loss, a receiver sensitivity great enough to provide dependable operation through a loss of 70 decibels is desirable.

A specific application of extensive use of tones for telemetering and load control is shown in Figure 9. The problem here is to keep the total load divided properly among three generators A, B, and C, and use as few carrier channels as practical. The load on each generator is to be telemetered to the load dispatcher at D, where load-control equipment sends raise and lower impulses back to the generating stations to keep the load divided as desired. These functions are accomplished thus: The carrier trans-



Figure 10. Typical power-line-carrier assembly for relaying, remote tripping, and point-to-point communication

mitters at stations A, B, and C are set at frequencies 1.5 kilocycles apart, and each is modulated with a different tone frequency for telemetering its generator load back to station D. The receiver at D is adjusted to receive a band wide enough to include the frequencies sent from A, B, and C, and the carrier side frequencies produced by the tones. Filters on the receiver at D separate the audio tones t_a , t_b , and t_c . The impulses provided by these tones operate the load-control equipment. Six audio tones are used to transmit the raise and lower load-control impulses from D to the generating stations A, B, and C on a single carrier frequency f_1 which may be widely different from f_2 , f_3 , and f_4 . At each generating station, a receiver is tuned to f_1 , and two tone filters pass the raise and lower impulses for that station. Only two carrier channels are needed; one channel 4.5 kilocycles wide to transmit

f_2 , f_3 , and f_4 , and another for f_1 with its six modulating audio tones. Double-frequency traps may be put in each end of the line if needed to allow satisfactory carrier reception under all conditions of system switching.

It will be noted in this example that the frequency separation of the transmitters at stations A, B, and C will cause major heterodynes of 1.5 and 3 kilocycles in the receiver at D. The audio tones t_a , t_b , and t_c must be sufficiently lower than 1.5 kilocycles that, for the maximum frequency drift of the transmitters, the major beat notes will still be far enough above the highest audio tone to produce no interference. There will be several minor heterodynes in the filter frequency band but of such low amplitude as to cause negligible interference.

The Equipment

From the preceding examples of the use of power-line carrier, it is evident that the equipment must be of flexible electrical and mechanical design to be readily adaptable to widely varying applications. Rack-and-panel construction provides flexibility, and each major piece of equipment is constructed as a separate unit on standard 19-inch-wide relay rack panels. All external connections are brought out to terminal strips on the rear of each unit to facilitate interconnections between units and still maintain a pleasing appearance.

Figure 10 illustrates a typical installation which combines pilot relaying, two tone functions, and point-to-point communication. The entire rack assembly can be swung out of the cabinet on hinges to facilitate inspection and provide accessibility to all components.

Conclusions

1. Audio tones provide an effective way of increasing the usefulness of a carrier channel.
2. Simultaneous operation of several auxiliary functions over a single carrier channel can be provided without interference by using a separate tone for each function.
3. Satisfactory carrier transmission through a higher noise level can be realized by using tone modulation.
4. Telephone communication can be used simultaneously with tone-operated functions by using suitable filters to separate the tone and voice frequencies.

References

1. POSSIBILITIES AND METHODS OF EXTENDING A CARRIER-CURRENT-RELAY CHANNEL TO OTHER

Some Aspects of Inductance When Iron Is Present

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Synopsis: It is the purpose of this paper to examine various definitions of inductance based on the application in which the term is used. Comparisons are made between the definitions as a function of magnetomotive force and flux density for the special case of dynamo-grade (2.75 per cent) silicon steel. The effects of hysteresis and eddy currents are discussed. Consideration is confined to iron magnetic circuits in which no air gap exists, so that practical applications of conclusions drawn are limited somewhat.

THE usual definition of inductance is based on the assumption that the saturation curve is a straight line. Other assumptions, which are implied though not necessarily expressed, are that there is no residual flux, no hysteresis, and no eddy-current loss. For these conditions all definitions yield the same value of a constant inductance.

There are, however, many applications where solid iron is used in the magnetic structure. In the majority of these applications it is economically necessary to run the iron at a density which makes the saturation curve depart considerably from that of a straight line. Under these practical conditions eddy currents, hysteresis, and saturation all contribute to make a definition which assumes that constant inductance often be considerably in error.

The importance of this subject will be appreciated when it is recognized that the actual duty on the contact tips of a d-c contactor may be several times greater than would be expected from calculated values of the load inductance.

Use of the Term "Inductance"

The term "inductance" is used in connection with many circuits and phenomena. Its use in electric machinery often has been defined and elaborated on. There are, however, many instances,

particularly in the industrial-control field, where a word is required to express a certain characteristic of a circuit, and that omnipresent word is "inductance." The following examples may be cited:

1. The build-up of current in the shunt field of a d-c machine, d-c contactor, relay, or brake is stated to depend on the time constant or ratio of inductance to resistance of the circuit.
2. The number of operations of which a contactor is capable depends to a great extent on the stored energy in the electric load which it is handling. In the case of a d-c contactor a large amount of this stored energy must be dissipated in the arc with consequent burning of tips, arcing horns, and chutes. The energy stored is stated to be one half of the product of inductance times current squared.
3. The rate of decay of d-c fields often is important when a field must be reduced rapidly or "killed." Here again decay is dependent supposedly on the time constant of the circuit.
4. When a contactor closes the tendency for the tips to weld or freeze depends on the rate at which the current builds up, and this usually is considered to be inversely proportional to the inductance of the circuit.
5. When a contactor interrupts an a-c circuit, the recovery voltage, after a current zero, rises at a rate which is dependent on the circuit inductance and capacitance.
6. In obtaining the inductance of an iron-core reactor it is common practice to read volts, amperes, and watts and to calculate the reactance and inductance from the data so obtained.

It will be shown in the following that for an iron-cored circuit the various in-

ductances enumerated previously may be considerably different from each other, so much so that large errors result if they are used interchangeably.

Common Definitions of Inductance

There are three definitions of L commonly used in the literature.¹ The first is in terms of flux linkages per ampere, that is

$$L = \frac{\Psi_o}{i} = \frac{N\Phi_o}{i} \quad (1)$$

In order that L be constant in equation 1, the condition must hold that flux is proportional to current. The second usual definition is to define L in terms of the back electromotive force by means of the equation

$$e = -L \frac{di}{dt} \quad (2)$$

The third definition is in terms of the energy stored in a magnetic field and is given by the equations

$$W = - \int e i dt = \int_0^i L i di = \frac{1}{2} L i^2 \quad (3)$$

Equations 1, 2, and 3 are used as the three basic definitions and give identical and constant values of L for the linear magnetization curve.

Although practically all textbooks and handbooks define inductance in one of these three ways, the majority (including the "American Standard Definitions of Electrical Terms" by AIEE) prefer to consider equation 2 as being basic.²⁻⁴

Equation 2 also may be stated

$$L = - \frac{e}{\frac{di}{dt}} = -e \frac{dt}{di} = N \frac{d\Phi_o}{di} \quad (4)$$

and L is defined in this way by several other authors.^{5,7}

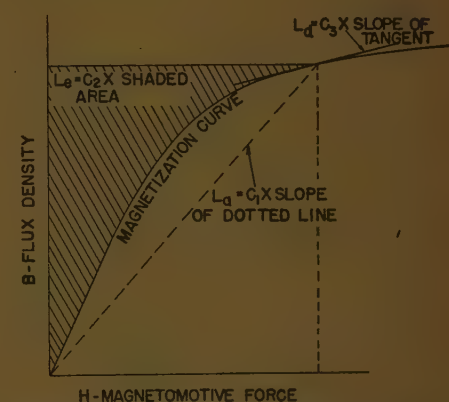


Figure 1. Geometrical interpretation of L_o , L_d , and L_e in terms of the d-c magnetization curve

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3. USES OF CARRIER CURRENT, M. E. Reagan. *Electric Journal*, June 1936.

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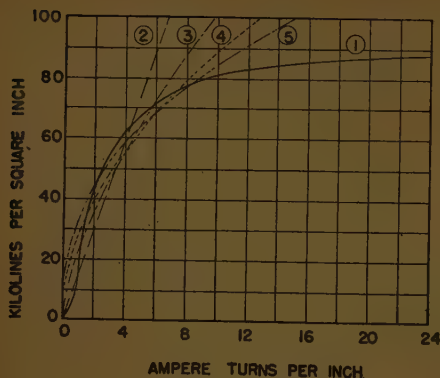


Figure 2. Comparison of the curves $H=KB^n$ with the magnetization curve of silicon steel

1. An actual curve for 2.75 per cent silicon steel
2. $H=(6.7)(10^{-3})B$
3. $H=(9.65)(10^{-3})B^{1.5}$
4. $H=(1.26)(10^{-3})B^2$
5. $H=(1.5)(10^{-4})B^{2.5}$

The "Standard Handbook for Electrical Engineers" edited by Knowlton lists both equations 2 and 3 as fundamental, calling L the coefficient of proportionality in each case.⁸

Equation 1 seems to be considered fundamental mainly by men concerned with the analysis of rotating machinery.⁹⁻¹¹

Some textbooks redefine their fundamental magnetic concepts entirely when they change from air-core to iron-core circuits.¹² One author¹³ expresses the opinion that L should not be introduced at all when the permeance of the circuit is variable.

Geometric Definition of Inductance

Another usual method of defining inductance¹⁰ is to express it as a function of the physical dimensions. These include the area, length, and permeability of the flux paths, and dimensions and turns in the coils. This leads to the expression

$$L = (\text{constant}) \left(N^2 \frac{\mu A}{l} \right) \quad (5)$$

which is useful only if the value of μ can be determined, and all the flux is considered to link all of the turns.

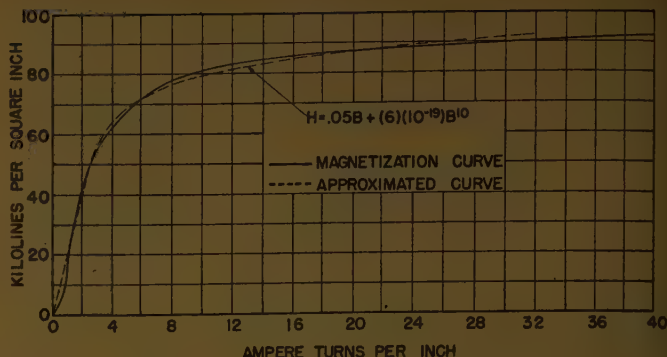
Definitions From Measurements

Besides these definitions (from which it is hard to evaluate L for the practical case), L may be defined from the method used to measure it. Two methods commonly used are

1. A-c measurements

$$E = I(R + jX_L) = I(R^2 + \omega^2 L^2)^{1/2} \quad (6)$$

Figure 3. Comparison of the d-c magnetization curve for 2.75 per cent silicon steel with the equation $H = 0.05B + (6)(10^{-10})B^{10}$



So

$$L = \frac{1}{\omega} \left(\frac{E^2}{I^2} - R^2 \right)^{1/2} \quad (7)$$

or if

$$R \ll \omega L$$

$$L = \frac{1}{\omega} \frac{E}{I} \quad (8)$$

2. Oscillogram of current change

$$E = iR + L \frac{di}{dt} \text{ for an } R-L \text{ series circuit} \quad (9)$$

So

$$i = \frac{E}{R} \left(1 - e^{-\frac{R}{L}t} \right) \text{ for current rise} \quad (10)$$

and

$$i = I_0 e^{-\frac{R}{L}t} \text{ for current decay if } L \text{ is constant} \quad (11)$$

From these equations

$$L = \frac{Rt}{\log_e \frac{I_f}{I_f - i}} \text{ for build-up} \quad (12)$$

and

$$L = \frac{Rt}{\log_e \frac{I_0}{i}} \text{ for decay} \quad (13)$$

Summary of Definitions

In order to differentiate between the quantities denoted by the common term "inductance" in the inductances taken from the preceding definitions, the follow-

ing subscripts and names have been given arbitrarily to L :

L_a = apparent inductance = Ψ_0/i from equation 1

L_d = differential inductance = $\frac{-e}{(di/dt)}$

$= N \frac{d\Phi_0}{di}$ from equations 2 and 4

L_e = inductance based on energy = $\frac{2W}{i^2}$ from equation 3

L_g = inductance based on geometry

$= (\text{constant}) \left(N^2 \frac{\mu A}{l} \right)$ from equation 5

L_{ac} = inductance based on rms readings

$= \frac{1}{\omega} \frac{E}{I}$ from equation 8

L_b = inductance based on time for current

build-up = $\frac{Rt}{\log_e \frac{I_f}{I_f - i}}$ from equation 12

L_{td} = inductance based on time for current

decay = $\frac{Rt}{\log_e \frac{I_0}{i}}$ from equation 13

Graphical Interpretation (Figure 1)

Figure 1 shows a magnetization curve plotted as B versus H . Since for a given magnetic circuit B is proportional to Ψ_0 and H to i , then

$$L_a = \frac{\Psi_0}{i} = (\text{constant}) \left(\frac{B}{H} \right)$$

so that L_a is proportional to the slope of the straight line drawn from the point of

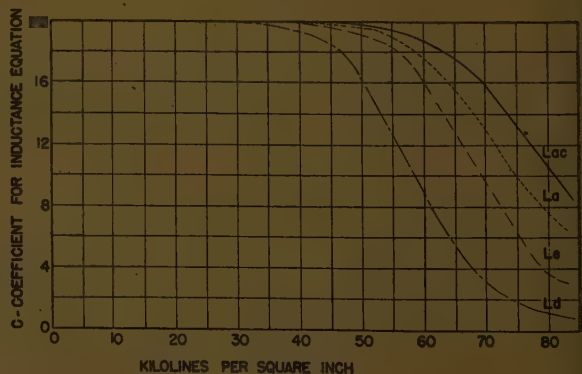


Figure 4. Variation of different inductances as a function of flux density

operation to the origin. This definition of L_a is very similar to the usual definition of μ which is defined as the ratio of B at a point to the H at that point.

Similarly

$$L_a=N\frac{d\Phi_o}{di}=(\text{constant})\left(\frac{dB}{dH}\right)$$

is proportional to the slope of the magnetization curve itself at a point and is analogous to μ_a , the differential permeability.

Also, since

$$\begin{aligned} W &= - \int ei \, dt = \int i \frac{d\psi}{dt} dt = \int i d\psi \\ &= (\text{constant}) \int H dB \end{aligned}$$

the energy stored in the magnetic field varies directly as the area between the magnetization curve and the vertical axis. Then L_a is proportional to this area for any given current.

Analytical Equivalent of a Magnetization Curve

An accurate analytical expression for the saturation curve is quite unwieldy, if it is desired to express B as a function of H . In order to approach a comparison of the different definitions of L mathematically, four flux versus current curves, namely $H=KB^n$ where $n=1, 1.5, 2$, and 2.5 were assumed. These are shown in Figure 2 compared with the magnetization curve for 2.75 per cent silicon steel. A reactor was assumed to consist of N turns on a closed core of length l and cross-sectional area A . Resistance, leak-

age, and hysteresis were neglected. The inductance was calculated as a function of the current for L_a, L_d , and L_o , and as a function of rms current and rms voltage for L_{ao} for each of the assumed B - H curves. See Appendixes II, III, IV, and V.

Results are shown in Table I. It should be noted that for L_a, L_d, L_o , and L_{ao} as a function of current, the expressions vary only in their numerical coefficient. L_a is the greatest, and L_d is the least. It is also interesting to note that, if L_{ao} is written in terms of voltage, L_{ao} becomes a function of frequency—a rather surprising result.

A more accurate approximation to the saturation curve is given by $H=K_1B+K_2B^{2.0}$ which is shown in Figure 3. Because of the difficulty involved in solving this equation for dB/dH or for B as a function of H , the inductances are compared in terms of B and B_{rms} (Table I). These equations are shown plotted against B in Figure 4 and against H in Figure 5. The coefficient C is the value by which the expression $(N^2A/l)10^{-5}$ must be multiplied in order to obtain L in henrys. See Appendix IIB.

For the case $H=K_1B+K_2B^{10}$ there does not seem to be a definite relationship between the different inductances, except that they all decrease quite rapidly as soon as the knee of the B - H curve is reached. Differential L drops the fastest and to the lowest value.

An air gap in the magnetic circuit would increase K_1 in the foregoing equation. Its effect would be to lower the C - H curves and to shift them to the right. All values of inductance would be

lowered except L_d which at certain currents may be higher with an air gap in the circuit than when the core is closed.

Inductance When Hysteresis Is Present

Figure 6 shows the variation of L_d and L_a with current, that is, with H , as a hysteresis loop for Nicaloi steel is traced. It should be noted that the coefficient C in the equation

$$L_d=C\frac{N^2A}{l}10^{-5} \tag{14}$$

varies from 4 to 175 over every half-cycle.

For L_a , C varies from minus to plus infinity which is a rather startling range for a quantity which is usually assumed constant. Figure 9 was drawn for Nicaloi, because it is a material which has a very low hysteresis-loop area and, therefore, is a close practical approach to a commercial material with no hysteresis. It is used extensively in transformers, reactors, and relays.

Figure 7 shows the same curves of L_a and L_d for a 2.75 per cent silicon steel. Here C in L_d varies from 0.8 to 4.7, and C in L_a , as before, goes from minus infinity to plus infinity.

Presence of Eddy Currents

Many oscillograms, taken on solid iron contactors and brakes to get current-time curves when a constant d-c voltage is applied, show a rapid initial rate of rise

Table I. Calculated Formulas of Inductance for Various Assumed Magnetization Curves

	$L_a=\frac{\Psi}{i}$	$L_d=\frac{d\Psi}{di}$	$L_o=\frac{2w}{i^2}$	$L_{ao}=\frac{1}{\omega}\frac{E_{rms}}{I_{rms}}$
$H=f(B_o)$	In Terms of Current i			In Terms of Rms Voltage
$H=KB_o^{1.0}$	$1.0\frac{N^2A}{Kl}$	$1.0\frac{N^2A}{Kl}$	$1.0\frac{N^2A}{Kl}$	$1.0\frac{N^2A}{Kl}$
$H=KB_o^{1.5}$	$1.0\frac{N^{2/3}A}{K^{1/3}l^{2/3}i^{1/3}}$	$0.67\frac{N^{2/3}A}{K^{1/3}l^{2/3}i^{1/3}}$	$0.80\frac{N^{2/3}A}{K^{1/3}l^{2/3}i^{1/3}}$	$0.94\frac{N^{2/3}A}{K^{1/3}l^{2/3}I^{1/3}}$
$H=KB_o^{2.0}$	$1.0\frac{N^{3/2}A}{K^{1/2}l^{3/2}i^{1/2}}$	$0.50\frac{N^{3/2}A}{K^{1/2}l^{3/2}i^{1/2}}$	$0.67\frac{N^{3/2}A}{K^{1/2}l^{3/2}i^{1/2}}$	$0.91\frac{N^{3/2}A}{K^{1/2}l^{3/2}I^{1/2}}$
$H=KB_o^{2.5}$	$1.0\frac{N^{7/5}A}{K^{2/5}l^{7/5}i^{2/5}}$	$0.40\frac{N^{7/5}A}{K^{2/5}l^{7/5}i^{2/5}}$	$0.57\frac{N^{7/5}A}{K^{2/5}l^{7/5}i^{2/5}}$	$0.88\frac{N^{7/5}A}{K^{2/5}l^{7/5}I^{2/5}}$
	In Terms of $B_{instantaneous}$			In Terms of B_m
$H=K_1B+K_2B^{10}$	$\left(\frac{N^2A}{K_1l}\right)\frac{10^{-5}}{1+\frac{K_2}{K_1}B^9}$			$\left(\frac{N^2A}{K_1l}\right)10^{-5}\left[1+0.94\frac{K_2}{K_1}B_m^9+0.35\left(\frac{K_2}{K_1}\right)^2B_m^{18}\right]^{-1/5}$

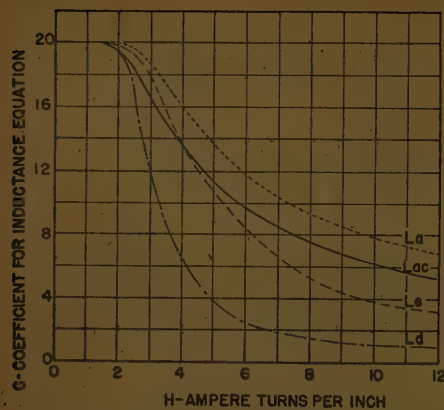


Figure 5. Variation of different inductances as a function of magnetomotive force

of current. This effect is attributed sometimes to remanent flux in the device and sometimes to eddy currents. Figure 8 is a copy of a typical oscillogram taken on a contactor having a magnetic circuit about 11 inches in length and average cross section of one square inch with a 0.015-inch air gap in the circuit. Tests taken of current build-up with both positive and negative remanent flux left in the circuit by previous operations showed practically no change in initial rise.

The values of inductance at different currents calculated from the oscillogram in a step-by-step process using the equation

$$L_d = \frac{E - Ri}{\frac{di}{dt}} \quad (15)$$

are shown in Figure 9.

Curves 1 and 2 of Figure 9 show the variation of L with current build-up and curve 3 with current decay (calculated from an oscillogram). It should be noted that curve 3 reads from right to left with respect to time. Although direct comparisons of curves 1 and 3 are impossible because of the hysteresis loop, it is still significant to notice the high inductance exhibited by curve 3 at zero current compared with the inductance shown by curve 1. This probably is due to the difference in the rate of current in the coil. In the former case the d-c arc was going out slowly, while in the latter case a sudden voltage inducing large eddy currents was applied.

Other data, not reproduced here, in which the current and flux rise in a series brake magnet were measured, have shown that the time required for the flux in the air gap to reach its final value is about ten times as long as the time required for the current to build up. This lag is attributable to the demagnetizing action

of the eddy currents and, of course, affects the inductance.

Inductance Based on Build-up and Decay of Current

Figure 10 shows calculated curves for the increase of current with time when a constant voltage is applied to a 2.75 per cent silicon-steel-core reactor, and saturation is taken into account, but hysteresis and eddy currents are neglected. Four such curves for different applied voltages are plotted. These curves were obtained by a step-by-step integration of the equation

$$E = Ri + L_d \frac{di}{dt} \quad (16)$$

where the equation $H = 0.05B + (6) \times (10^{-19}) \times B^{10}$ was used instead of the true

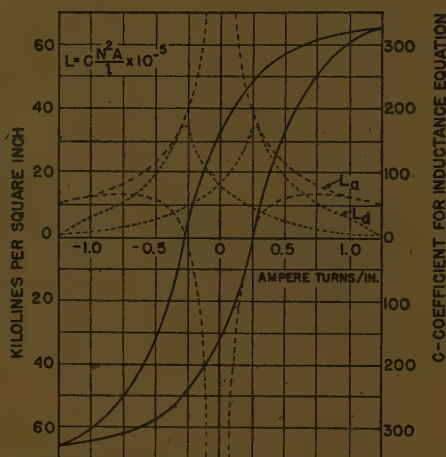


Figure 6. Variation of L_a and L_d over a complete cycle of the hysteresis loop of Nicoloi

B - H curve of the material. This was done, so that equivalent inductances (L_{eq}) calculated from the curves of Figure 10 could be compared with those obtained by calculation from other definitions. Equivalent inductance means that value of inductance which, if constant, would allow the current to reach the same percentage of its final value in the same time that it does in Figure 10. From these curves of Figure 10 the value of time at which the current was equal to 90 per cent of its final value was read. When equation 10 was used, the value of L_{eq} , the equivalent or constant inductance, was calculated. The same was done for current equal to 63 per cent of its final value. When these calculated values of L_{eq} were used, the curves 2 and 3 of Figure 12 were plotted. The difference between L_a , the usual definition for inductance for a d-c field, and the constant inductance, which should

be used to give the true time of build-up, is shown clearly.

Curves 1 and 4 of Figure 12 are calculated from the decay curve of Figure 11. These current-decay curves were obtained in the same way the current-rise curves were found, that is, by a step-by-step integration of equation 16 when $E=0$ for the magnetization curve $H = 0.05B + (6)(10^{-19})B^{10}$.

It should be noted that L_a in Figure 12 falls between curves 1 and 3 for the 90 per cent case and also between curves 2 and 4 for the 63 per cent case, that is, the apparent inductance is somewhere between the inductance calculated from build-up and decay.

If currents which are closer to 100 per cent of final are chosen, curve 3 will be lower and curve 1 will be higher, showing more and more error between apparent inductance and the constant inductance which gives the correct build-up or decay time.

Experimental Verification

An experimental verification of these theoretical curves is shown in Figure 13 which is a copy of an oscillogram. This was taken to measure the inductance of the field of a 50-horsepower synchronous motor, so that an equivalent circuit could be built in order to test the interrupting ability of switches of different ratings. From the slope of the current-time curve the inductance was computed by equation 14 and is shown plotted in Figure 14. It may be noted that the

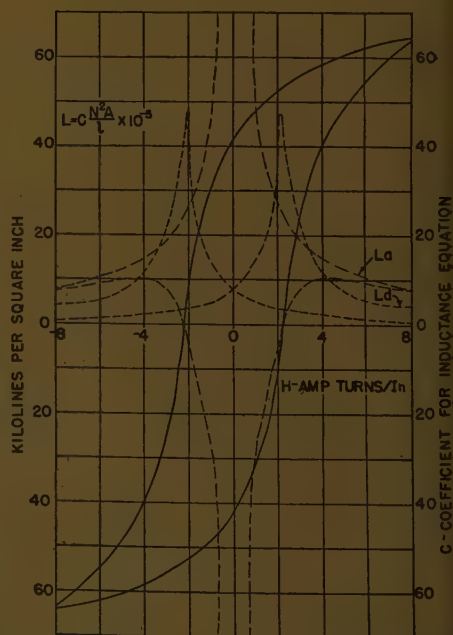


Figure 7. Variation of L_a and L_d over a complete cycle of the hysteresis loop of 2.75 per cent silicon steel

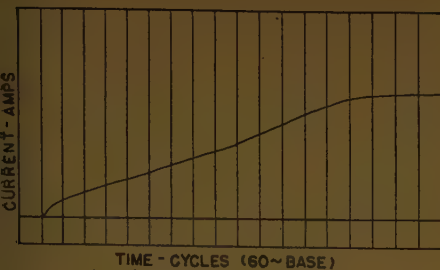


Figure 8. Traced copy of an oscillogram showing current build-up with constant applied voltage in a d-c solid-iron contactor with 0.015-inch air gap

current-time curve is very similar to those shown in Figure 10. The inductance of this machine had been given as 12 henrys; the oscillogram showed a range from nine to three henrys.

Conclusions

1. Although comparisons have been made in this paper between various definitions of L on the basis of a closed circuit and silicon steel, similar results can be obtained as readily for any other steel and circuit containing an air gap.

2. The assumption, that inductance is a constant in an iron magnetic circuit where the flux density is of the usual practical value, and the air gaps are small, leads to large errors. Saturation cannot be neglected merely to obtain a mathematical solution of a problem, for the solution then bears little relation to the actual case.

3. The true inductance of a circuit, in the sense of a back electromotive force, is the differential inductance. There is much work to be done to calculate differential inductance for magnetic circuits which have air gaps. Results probably can be expressed usefully in terms of mils of air gap per inch of iron. Such data on machines are necessary, if accurate control of those machines is to be precalculated.

4. Observation of Figures 4, 6, and 12 shows the wide variations in inductance, depending on the method of calculation or measurement. The particular value to be used depends on the application to which it is applied.

5. The statement, that inductance is a function of the physical dimensions of a circuit and of μ , throws the whole definition into an evaluation of the value of μ and is for that reason of little use.

6. The widespread use of a time constant based on flux linkages per ampere, that is L_a , often leads to results considerably in error. With the great increase in speeds of voltage response called for on a large variety of industrial-control applications, such as variable-voltage planer drives or amplidyne-forced steel-mill motors, it is becoming increasingly necessary for the circuit designer to have more information regarding current build-up in the d-c fields. For accurate field control as a function of time, it is necessary to know an equivalent inductance (L_a) which will give the correct build-up time.

Figure 9 (right). Variation of L_d with current for the d-c contactor of Figure 8

1. L_d calculated from current build-up after contactor had carried current in the negative direction. Air gap is 0.015 inch

2. L_d calculated from current build-up after contactor had carried current in the positive direction. Air gap is 0.015 inch

3. L_d calculated from an oscillogram of current decay. Air gap is 0.015 inch

4. Same as 1 but with an air gap of 0.375 inch

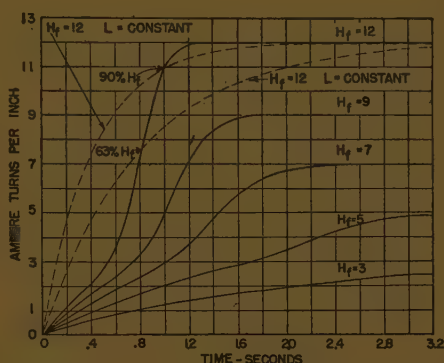


Figure 10. Current-time build-up curves calculated from $H=0.05B+(6)(10^{-19})B^{10}$ for various applied voltages compared with theoretical constant-inductance build-up curves

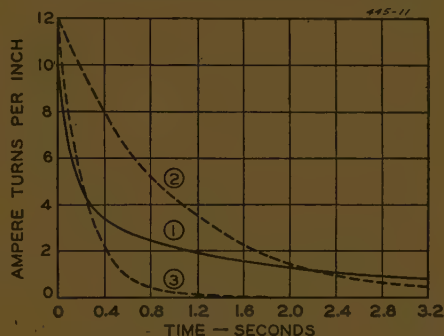


Figure 11. Current-decay curves

1. Current-time-decay curve for the material given by $H=0.05B+(6)(10^{-19})B^{10}$
2. H -versus-time curve for the constant inductance (L_d) which crosses curve 1 at 10-per cent of its original value
3. H -versus-time curve for the constant inductance (L_d) which crosses curve 1 at 37 per cent of its original value

7. In specifying the interrupting ability of contactors which handle motor loads, it would seem advisable, in order to obtain comparative data, to set up L/R ratios for air-core reactors rather than to specify motor loads. Much work still remains to be done to identify the effect of a variable inductance load on both a-c and d-c interruption, so that equivalent air-core loads can be used for test purposes.

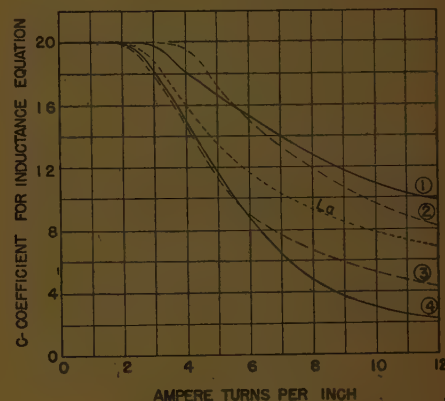
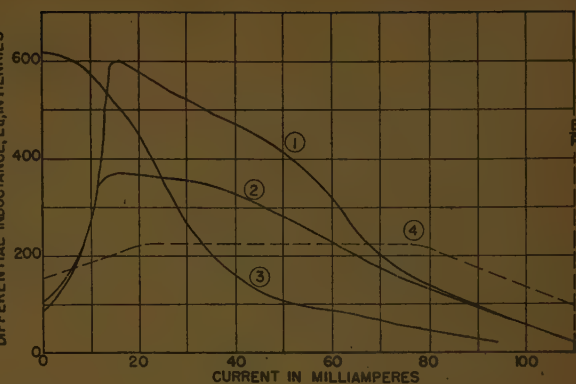


Figure 12. Variation of L_d and L_b with magnetomotive force

1. L_d for decay time at which $i=10$ per cent i_0
2. L_b for build-up time at which $i=63$ per cent i_f
3. L_b for build-up time at which $i=90$ per cent i_f
4. L_d for decay time at which $i=37$ per cent i_0

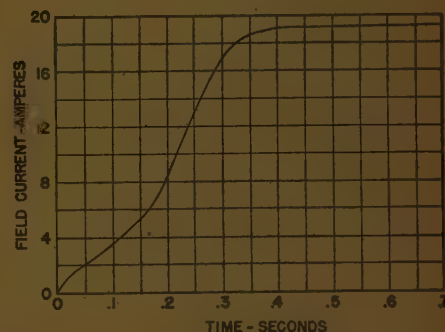


Figure 13. Traced copy of an oscillogram showing current build-up versus time at constant applied voltage for a 50-horsepower synchronous-motor field

8. In the majority of d-c circuits containing solid iron, eddy currents affect the initial rate of current rise, so that a calculated inductance, such as L_a , is not a dependable criterion for severity of the circuit with respect to tip welding. To obtain comparative data air-core inductances should be specified.

9. The authors have made no investigations as yet on a circuit which contains motor or reactor loads to find the inductance

which, together with the capacitance of the system, determines the natural frequency of the circuit and so critically affects a-c circuit interruption. Such an investigation may lead to still another inductance.

10. Electrical engineering courses in college could include profitably more work on magnetic circuits. Very few textbooks even admit the presence of iron in their treatment of the classical current rise and decay in a d-c circuit, and yet in industry few examples can be found where iron is not a dominant factor.

It is realized that the foregoing analysis is by no means complete, and that much work remains to be done. Hysteresis and eddy currents have been taken into account in some places and neglected in others. Leakage has not been considered at all. It is hoped, however, that this work will serve to stimulate interest in the examination of iron circuits from the point of view of the control apparatus which must handle those circuits and also will lead to AIEE definitions of inductance when iron is present.

Appendix I. Nomenclature

- L =inductance in henrys
- e =voltage at time t
- i =instantaneous value of current
- Φ_o =flux linkages—webers times turns
- Ψ =flux linkages—kilolines times turns
- t =time—seconds
- W =energy—joules
- I =rms current
- E =rms voltage or d-c voltage
- Φ_o =flux in webers
- Φ =flux in kilolines
- B_o =flux density in webers per square inch
- B =flux density in kilolines per square inch
- B_m =maximum value of flux density in kilolines per square inch
- I_o =initial value of current for d-c current decay= E/R
- I_f =final value of current build-up case= E/R
- R =resistance in circuit
- H =magnetizing force—ampere turns per inch

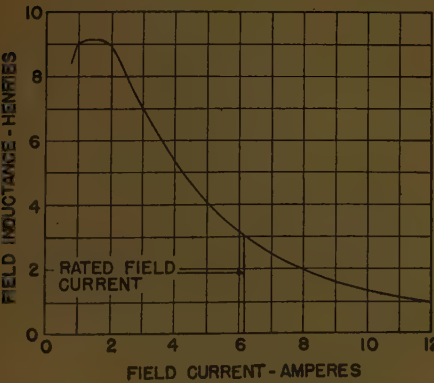


Figure 14. Inductance (L_d) of the synchronous-motor field calculated from Figure 13

- H_f =final value of magnetomotive force in a d-c circuit
- l =length of the magnetic path in inches
- A =cross section of the magnetic path in square inches
- $L_a, L_d, L_e, L_g, L_{ac}, L_{ab}, L_{td}$ are defined in the text in the paragraph "Summary of Definitions"
- $\omega=2\pi f$ where f is the frequency
- μ =permeability
- A =area of an iron circuit in square inches

Appendix II

A. Calculation of L_a when $H=KB_o^n$. From equation 1, which is the defining equation for L_a

$$L_a = \frac{N\Phi_o}{i} = \frac{NAB_o}{i} \quad (17)$$

Substituting $H=KB_o^n$ into equation 17 yields

$$L_a = \frac{NA}{i} \left(\frac{H}{K} \right)^{\frac{1}{n}} \quad (18)$$

and

$$H = \frac{Ni}{l} \quad (19)$$

so that

$$L_a = \frac{NA}{i} \left(\frac{Ni}{lK} \right)^{\frac{1}{n}} \quad (20)$$

Substitution of $n=1.0, 1.5, 2.0$ and 2.5 , into equation 20 gives the formulas for L_a shown in Table I.

B. Calculation of L_a when $H=K_1B+K_2B^{10}$. By substituting the value of i from equation 19 in equation 17

$$L_a = \frac{N^2AB_o}{lH} = \frac{N^2AB}{lH} 10^{-8} \quad (21)$$

$$= \frac{N^2A 10^{-8}}{lK_1 \left(1 + \frac{K_2}{K_1} B^9 \right)} \quad (22)$$

Appendix III

A. Calculation of L_e when $H=KB_o^n$

$$W = \int ei dt \text{ and } e = NA \frac{dB_o}{dt}$$

so that

$$W = NA \int i dB_o$$

Now

$$B_o = \left(\frac{H}{K} \right)^{\frac{1}{n}}$$

and

$$dB_o = \frac{1}{n} \frac{H^{\frac{1}{n}-1}}{K^{\frac{1}{n}}} dH \quad (23)$$

$$dB_o = -\frac{1}{nK^{\frac{1}{n}}} \left(\frac{iN}{l} \right)^{\left[\frac{1}{n}-1 \right]} di \quad (24)$$

and

$$W = \frac{NA}{nK^{\frac{1}{n}}} \left(\frac{N}{l} \right)^{\frac{1}{n}} \int i^{\frac{1}{n}} di = \frac{AN}{K^{\frac{1}{n}} l^{\frac{1}{n}}} \left(\frac{i^{\left[\frac{1}{n}+1 \right]}}{\frac{1}{n}+1} \right) \quad (25)$$

Since

$$W = \frac{1}{2} Li^2$$

then

$$L = \frac{2W}{i^2} = \frac{2AN}{i^2} \frac{i^{\left[\frac{1}{n}+1 \right]}}{\frac{1}{n}+1} \frac{1}{l^{\frac{1}{n}}} \quad (26)$$

Substitution of $n=1.0, 1.5, 2.0$, and 2.5 in equation 26 yields the formulas shown for L_e in Table I.

B. Calculation of L_e when $H=K_1B+K_2B^{10}$

$$W = e i dt = lA \int H dB_o$$

and

$$L = \frac{2W}{i^2} = \frac{2AN^2}{lH^2} \int H dB_o \quad (27)$$

$$= \frac{2AN^2 10^{-8}}{lH^2} \int (K_1B + K_2B^{10}) dB$$

$$= \frac{AN^2 10^{-8}}{l} \frac{(K_1B^2 + 0.182K_2B^{11})}{K_1^2B^2 + 2K_1K_2B^{11} + K_2^2B^{20}}$$

$$= \frac{AN^2}{lK_1} \frac{\left(1 + 0.182 \frac{K_2}{K_1} B^9 \right) 10^{-8}}{1 + 2 \frac{K_2}{K_1} B^9 + \left(\frac{K_2}{K_1} \right)^2 B^{18}} \quad (28)$$

Appendix IV

A. Calculation of L_d when $H=KB_o^n$. From equation 4 which defines L_d

$$L_d = N \frac{d\Phi_o}{di} = NA \frac{dB_o}{di} \quad (29)$$

where

$$B_o = \left(\frac{H}{K} \right)^{\frac{1}{n}} = \left(\frac{Ni}{lK} \right)^{\frac{1}{n}}$$

Then

$$\frac{dB_o}{di} = \frac{1}{n} \left(\frac{N}{lK} \right)^{\frac{1}{n}} i^{\left[\frac{1}{n}-1 \right]} \quad (30)$$

and

$$L_d = \frac{NA}{n} \left(\frac{N}{lK} \right)^{\frac{1}{n}} \frac{1}{i^{\frac{1}{n}}} \quad (31)$$

which is equal to L_a/n . Substitution of $n=1.0, 1.5, 2.0$, and 2.5 into equation 31 gives the formulas for L_d in Table I.

B. Calculation of L_d when $H=K_1B+K_2B^{10}$

$$L_d = \frac{Nd\Phi_o}{di} = \frac{N^2A}{l} \frac{dB_o}{dH} = \frac{N^2A}{l} \frac{dB}{dH} 10^{-8} \quad (32)$$

$$= \frac{N^2A}{l} \frac{10^{-8}}{K_1 + 10K_2B^9}$$

$$= \frac{N^2A}{lK_1} \frac{10^{-8}}{\left(1 + 10 \frac{K_2}{K_1} B^9\right)} \quad (33)$$

Appendix V

A. Calculation of L_{ac} when $H=K(B_o)^n$. Assuming no resistance or hysteresis

$$L_{ac} = \frac{1}{\omega} \frac{E}{I} = \frac{1}{\omega} \frac{E_m}{(2)^{1/2} \left[\frac{1}{T} \int_0^T i^2 dt \right]^{1/2}} \quad (34)$$

Now

$$e = NA \frac{dB_o}{dt} = E_m \sin \omega t$$

when B_o is in webers per square inch, so that

$$B_o = \frac{-E_m}{NA\omega} \cos \omega t \quad (35)$$

Now

$$i = \frac{lH}{N} = \frac{lKB_o^n}{N} \quad (36)$$

$$= \frac{lK}{N} \left(\frac{-E_m}{NA\omega} \cos \omega t \right)^n \quad (37)$$

When $n=1, 1.5, 2$, and 2.5 is substituted in equation 36, and equation 34 is evaluated, the results shown in Table I for L_{ac} in terms of E_m are obtained.

Substituting $\omega LI=E$ in the equations so derived yields the formulas shown for L_{ac} in terms of I in Table I.

B. Calculation of L_{ac} when $H=K_1B+K_2B^{10}$

$$L_{ac} = \frac{1}{\omega} \frac{E}{I} = \frac{NAB_m 10^{-8}}{\sqrt{2} I} = \frac{0.707 NAB_m 10^{-8}}{I} \quad (38)$$

Now

$$I = \left(\frac{4}{T} \int_0^T i^2 dt \right)^{1/2} = \frac{2l}{N} \left(\int_0^T \frac{1}{4} H^2 dt \right)^{1/2} \quad (39)$$

Substituting for H as a function of B we obtain

$$I = \frac{2l}{N} \left(\int_0^T \frac{1}{4} (K_1^2 B_m^2 \cos^2 \omega t + 2K_1 K_2 B_m^{11} \times \cos^{11} \omega t + K_2^2 B_m^{20} \cos^{20} \omega t) dt \right)^{1/2} \quad (40)$$

Evaluation of this expression (Hudson's manual equation 330)

$$I = \frac{0.707 l K_1 B_m}{N} \left[1 + 0.942 \frac{K_2}{K_1} B_m^9 + 0.352 \left(\frac{K_2}{K_1} \right)^2 B_m^{18} \right]^{1/2} \quad (41)$$

$$L_{ac} = \frac{N^2 A}{K_1 l} (10^{-8}) \left[1 + 0.942 \frac{K_2}{K_1} B_m^9 + 0.352 \left(\frac{K_2}{K_1} \right)^2 B_m^{18} \right]^{-1/2} \quad (42)$$

By plotting equation 41 for I versus B_m and equation 42 for L_{ac} versus B_m , the plot

of L_{ac} versus I is obtained, which is shown in Figure 5.

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A Magnetic-Type Air Circuit Breaker for 15,000-Volt Services

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Synopsis: In the development of the five-kilovolt Magne-Blast air circuit breaker, it was shown that rapidly increased arc resistance was extremely effective in circuit interruption. This paper describes an extension of that principle in the development of a Magne-Blast circuit breaker for 15-kv services with an interrupting rating of 250,000 kva. The higher electrical resistance of the arc necessary for this voltage has been made possible by an increase in the thermal efficiency of the interleaving arc chute. The arc chute which provides this greater efficiency is discussed in some detail. The design of the breaker is described briefly as well as its application to metal-clad switchgear. Test data and representative oscillograms are submitted to substantiate the interrupting rating assigned to this breaker.

MODERN switchgear equipments with moderate-voltage air circuit breakers have been used to considerable advantage during the recent period of industrial expansion. Under the severe service conditions of this greatly accelerated war program, magnetic-type air circuit breakers have proved their worth in reliable operation with a minimum of maintenance. The trend toward air circuit breakers for all moderate distribution voltages has been hastened by this experience, and demands for an extension of the line are real. The design history and performance characteristics of a development that eventually will extend the application of magnetic-type air circuit breakers to 15-kv service with interrupting capacities of 250,000 and 500,000 kva are presented here.

The first Magne-Blast air circuit breakers were introduced for 2,300-to 5,000-volt service. Intended to replace the conventional oil circuit breaker of comparable ratings, these breakers were designed as the removable switching unit of modern vertical-lift metal-clad switchgear. These breakers emphasized the beneficial effects of rapidly increasing the resistance of the arc prior to inter-

ruption of a-c circuits, both from the standpoint of current reduction and reduction of the rate of rise of recovery voltage. Heretofore, it had been considered generally that increasing arc resistance only increased the energy that had to be dissipated in the interrupter and was therefore to be avoided.

Since being described before the Institute in 1939,¹ additional sizes had been developed to include 50,000 to 150,000 kva at 5 kv and 250,000 kva at 7.5 kv. The operating record of the several thousand Magne-Blast breakers now in service has been so satisfactory that it was imperative to continue this development into the 15-kv range at 250,000 kva and higher. An extensive development program was therefore initiated to develop a 15,000-volt air circuit breaker. How it

has been possible to extend the Magne-Blast principles of interruption in the development of such a 15,000-volt air circuit breaker having 250,000-kva interrupting capacity is described in the following sections. A brief description of the breaker and representative oscillograms also are presented.

Development of the 15-Kv Arc Chute

The primary problems in the development of an arc chute suitable for a 15-kv magnetic air circuit breaker are those of providing sufficient arc cooling to insure positive interruption and sufficiently high dielectric strength to withstand the insulation requirements of this voltage while still maintaining the approximate space requirements of the corresponding oil circuit breaker. The general form of the interleaving arc chute developed for the lower-voltage Magne-Blast breakers provided an interrupter that promised to interrupt considerable current at much higher voltages. This arc chute has parallel fins which project alternately from the two inner sidewalls. As the arc is forced magnetically into the arc chute, it meets fins of gradually-increasing

Table I. 15,000-Volt 250,000-Kva Magne-Blast Circuit Breaker

Test Number	Test Voltage	Maximum-Phase Rms Amperes (Closing)	Maximum-Phase Rms Amperes (Initial in Arc Interrupted)	Arcing Time (Cycles)	Trip Impulse to Interruption	Three-Phase Kva Interrupted
Three-Phase Interrupting Tests—Opening Tests						
1-4	14,500		4,600	0.8	2.9	120
5-8	14,500		8	0.8	2.9	200
9-12	14,500		17	1.4	3.6	440
13-22	14,500		38	2.0	4.0	960
23-32	14,500		74	2.1	4.2	1,600
33-36	14,500		130	2.0	4.0	3,300
37-40	14,500		270	2.2	4.3	6,800
41-44	14,500		600	2.2	4.3	15,000
45-46	14,500		1,990	2.1	4.3	50,000
47	14,500		3,000	1.7	3.9	75,000
48	14,500		4,800	1.4	3.8	120,000
49	14,500		10,300	1.3	3.6	260,000
50	14,500		9,300	1.0	3.3	240,000
51	14,500		10,900	1.1	3.3	270,000*
52	10,000		9,700	1.1	3.4	170,000
53	11,000		12,200	0.9	3.2	230,000
54	11,000		15,100	0.9	3.2	290,000
55	14,500		2,200	1.8	4.1	55,000
56	14,500		5,500	1.3	3.6	140,000
57	14,500		10,500	1.0	3.8	260,000
58	14,500		1,710	1.9	4.2	43,000
59	14,500		11,400	1.0	3.1	290,000
Three-Phase Trip-Free Closing—Opening Tests						
60	14,500	2,500	1,670	1.9	4.3	42,000
61	14,500	2,200	1,780	1.8	4.1	45,000
62	14,500	7,700	5,900	1.4	3.4	150,000
63	14,500	12,600	9,200	1.2	3.2	230,000
Three-Phase Two-Operation Duty Cycle—15-Second Reclosing						
64a	14,500	12,600	10,200	1.5	3.8	260,000
b	14,500		12,200	1.2	3.5	310,000**
Three-Phase Interruption Tests—Opening Tests						
65	14,500		8,100	1.3	3.7	200,000
66	14,500		6,700	1.4	3.7	170,000
67	14,500		9,600	1.3	3.5	240,000
68	11,000		17,000	1.3	3.6	320,000
69	11,000		14,200	1.4	3.6	270,000
70	11,000		14,500	1.4	3.7	280,000
71	11,000		11,200	0.9	3.1	210,000

* See Figure 8. ** See Figure 9.

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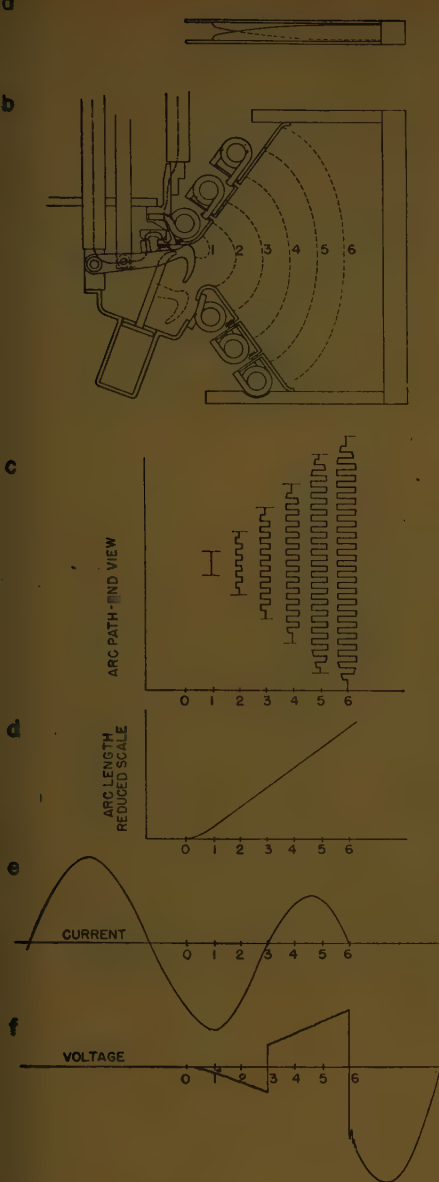


Figure 1. Schematic view of arc interruption in 15,000-volt Magne-Blast arc chute

- Plan view of arc chute showing gradual increase in depth of interleaving fins
- Successive positions of arc as it is forced into chute. Blowout coils are inserted one at a time as arc travels along arc runners
- Cross-section views of successive arc positions
- Progressive increase of length of arc—reduced scale
- Short-circuit current showing reduction effected by resistance of long arc prior to interruption
- Voltage across contacts of breaker which is zero with breaker closed. As contacts part and arc increases in length, its increasing resistance produces a rising arc-voltage drop. At current interruption voltage assumes 60-cycle line-voltage value
- The strength of the transverse magnetic field available for forcing the arc into the chute.
- The spacing of the arc runners for sustaining recovery voltage.

(a). Both the length of the arc path and the thermal efficiency of the interleaving fins in the arc chute are effective in increasing the arc resistance prior to current zero. The short-circuit current is reduced by the introduction of this arc resistance into the circuit, the reduction often being as much as 25 to 30 per cent of current values prior to contact parting. The instantaneous recovery voltage is reduced likewise in magnitude, for the current zero is advanced from its normal lag of 90 degrees toward or beyond the normal voltage zero. For a given value of short-circuit current, this arc resistance must be increased directly with the applied voltage to obtain the same percent-

age current reduction and instantaneous recovery-voltage reduction.^{2,3}

Item *a*, or the relationship between voltage-interrupting characteristics and the length of the serpentine arc path can be checked easily by tests. To do this two 7,500-volt arc chutes and their associated breaker parts were connected in series and opened simultaneously on a 15,000-volt connection in the testing laboratory. These tests demonstrated that two chutes could interrupt the same current as a single chute at double the voltage of a single chute. Cathode-ray oscillographic records illustrated a characteristic of particular interest, for they showed that the recovery voltage immediately following interruption divided equally between the two arc chutes. Within a very short interval this division was modified to values determined by the relative capacitances of the separate arc chutes and contact structures. The resistances of the continuous interleaving hot gas path across each chute immediately following interruption provided an efficient potential divider. It is this same resistance path in a single arc chutes that limits the rate of rise of recovery voltage immediately after current interruption. During a long history of tests on these breakers, this phenomena always has limited effectively the rate of rise of recovery voltage to 300 volts per microsecond or less, regardless of actual circuit characteristics.

In the art of circuit interrupters there are numerous instances where circuit breakers, inherently lacking in this desirable characteristic, have used external resistors to limit the rate of rise of recovery voltage to moderate values.

The length of the serpentine arc path can be increased by providing additional

depth extending deeper and deeper into the matching slots between the fins of the opposite side. Where the fins interleave across each other, the arc is folded back and forth gradually into a serpentine path as it proceeds into the arc chute, where it is lengthened rapidly, and its resistance is increased greatly through the transfer of thermal energy to the arc-chute surfaces. The effect of the interleaving arc chute in increasing the length and resistance of the arc and the effect of this resistance in reducing the short circuit and instantaneous recovery voltage are shown schematically in Figure 1.

Experience gained in the development of 5,000- and 7,500-volt Magne-Blast breakers showed that the voltage which could be interrupted by an interleaving arc chute is proportional to

- The length of serpentine arc path.
- The thermal effectiveness of the interleaving fins in removing heat per unit length of arc.

Figure 2. Interleaving arc chutes for a 15,000-volt 250,000-kva Magne-Blast circuit breaker—one chute opened to show contour of interleaving fins



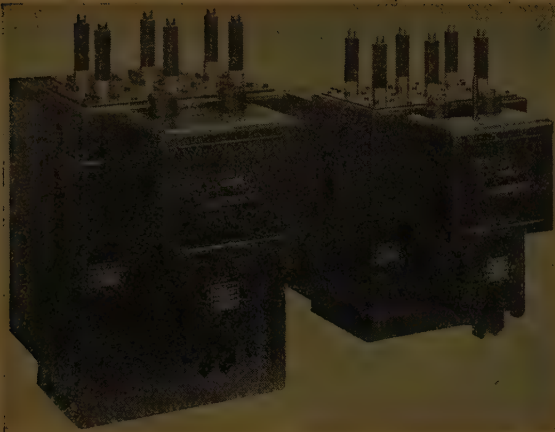


Figure 3 (left). Comparison of 15,000-volt and 7,500-volt Magne-Blast circuit breakers showing similarity of design features

Both breakers rated 250,000-kva interrupting capacity

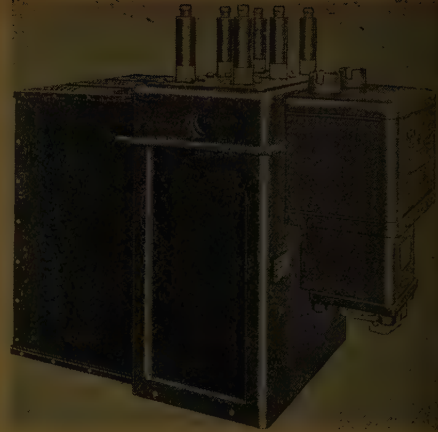


Figure 4

(a—right). 1,200-ampere Magne-Blast air circuit breaker for 15,000-volt service. Rated interrupting capacity 250,000 kva

or deeper fins. Increased fin depth is undesirable, as such a design necessarily dictates a wider chute. Here the efficiency of the magnetic system diminishes with the necessary increase in the gap spacing between the magnetic side plates or pole pieces. Additional fins, however, can be added without adding directly to the arc-chute size. Both thinner fins and a reduced spacing between fins add to the arc length directly without increasing the space requirements of the chute.

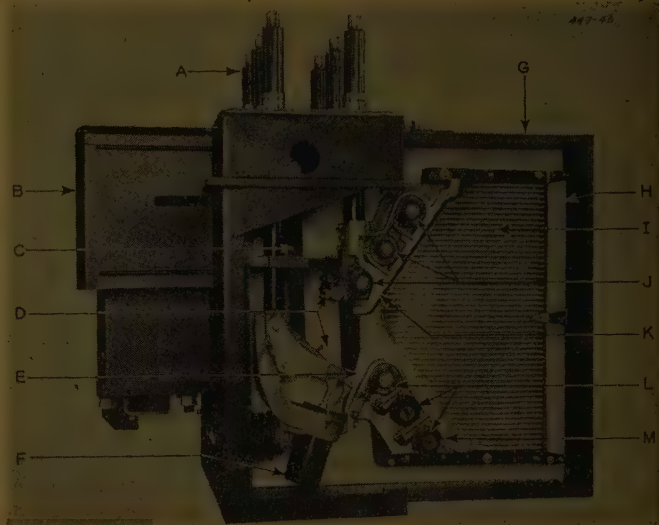
(b). The thermal effectiveness of the fins is increased also by moving the fins closer together, which flattens the normal cylindrical arc. The magnetic forces within the arc itself, however, try to return it to circular cross section which greatly increases the intimacy of the contact between the arc and fin surface. These phenomena are extremely effective in extracting heat from the arc. Figure 2 shows the interleaving arc chutes as developed for a 15-kv Magne-Blast breaker having 250,000-kva interrupting capacity. From this illustration the close proximity of the fins to the narrow interleaving path for the arc may be seen.

(c). As the thermal effectiveness of the fins is increased, the arc must be moved at correspondingly greater speeds to prevent excessive fin temperatures. The speed of the arc at any point, however, is proportional to the strength of the magnetic field at that point.

The strength of this magnetic field is a function of the current and the number of turns in the series blowout coils, the cross-sectional area of the iron-pole pieces, and the distance away from the coils. Six blowout coils are used to obtain a magnetic field of maximum flux density over the entire area of the arc chute. These coils are inserted one at a time as the arc travels along the diverging arc runners. Flux measurement tests have shown that, except for very small arc chutes, a much denser more uniform

(b). Cutaway view of circuit breaker through one pole showing arrangement of contacts, arc runners, series blowout coils, one side of interleaving arc chute, and muffler

- A. Herkolite bushings
- B. Solenoid operating mechanism
- C. Operating rod
- D. Primary contacts
- E. Arcing contacts
- F. Piston air booster
- G. Removable box barrier
- H. Muffler
- I. Interleaving arc chute
- J. Upper series blowout coils



- K. Upper arc runner
- L. Lower series blowout coils
- M. Lower arc runner

magnetic field can be obtained with several series coils distributed along the entire runner rather than by a single powerful series coil. This is due to the high values of flux leakage unavoidable in such large air-gap circuits, where the effective flux density reduces approximately as the square of the distance away from the coil. Superspeed photographs taken at the rate of 60,000 frames per second of actual arc interruptions also have shown that it is necessary to distribute these blowout coils to obtain uniform arc speed into the chute.

Design Features of the 15-Kv Breaker

During the early stages in the development of this air circuit breaker for 15-kv service, a number of different arrangements of interleaving arc chutes were tested that varied considerably from those used

on the original Magne-Blast-type circuit breaker. Although some of these designs were of early promise, none were so compact and so accessible as the conventional Magne-Blast arrangement. It is of interest that a revision of the original form of the Magne-Blast design was completely successful when the lengths of the arc path, thermal efficiency, magnetic field, and arc runner gap were scaled to satisfy the requirements for 15-kv service. Figure 3 illustrates the comparative sizes and design characteristics of one of the earliest (for 7,500-volt service) and the latest (for 15,000-volt service) circuit breakers of this type. All essential features are common to both ratings. The operating mechanism is still in an accessible position in front of the breaker; arc chutes and box barriers extend to the rear, and the entire unit is well adapted for vertical-lift metal-clad equipments. Figure 4a shows a 1,200-ampere 15-kv Magne-Blast breaker for 250,000 kva, and Figure 4b shows the cutaway cross section through one pole illustrating the arrangement of arc chutes, contacts, blowout coils, and so forth.

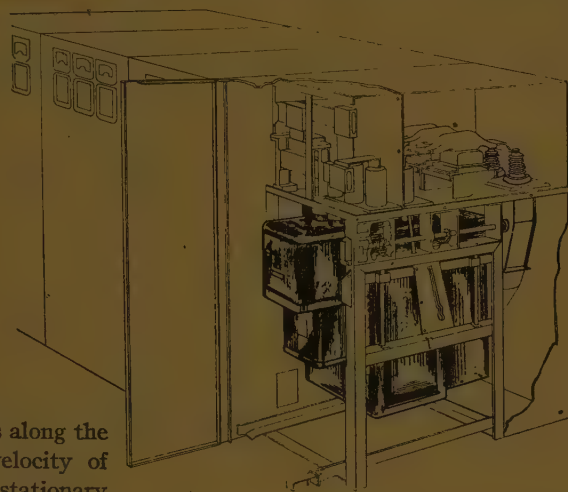
When the breaker is tripped the moment an arc is established, it leaves



(a—above). Circuit breaker and associated vertical-lift metal-clad switchgear unit

Figure 5

(b—right). Cutaway sketch showing circuit breaker elevated in place in metal-clad compartment



the arcing contacts and travels along the arc runners at an average velocity of 75 feet per second. It is never stationary and moves too rapidly to do any appreciable burning on the surfaces of either the contacts or the runners. Deterioration is reduced so greatly that, even at the maximum interrupting current rating of 14,000 amperes, several hundred circuit interruptions may be completed without requiring maintenance or replacement of arcing surfaces. It was, therefore, desirable to design the contact structure and breaker mechanism with a mechanical life commensurate with this arcing surface life. A new design contact structure has been developed in which both the primary contacts and the arcing contacts pivot on silver-alloy washers. This construction eliminates entirely the need of any flexible braid connections. Fifty thousand mechanical operations made on this type of silvering pivot have shown it to be very resistant to wear. This long operating life provides a breaker which is suited just as ideally to industrial applications calling for highly repetitive operations, such as arc-furnace or rolling-mill motor control, as it is to central-station feeder protection where service continuity is the prime requisite.

As the magnetic-field strength available for driving the arc into the arc chute in any series-coil magnetic breaker is directly proportional to the current being inter-

rupted, this magnetic driving force is always inherently weak when interrupting very light currents, particularly transformer magnetizing currents. To maintain the same high arc speeds and short arcing times when interrupting very light currents, as when interrupting heavy current, a supplemental air booster is provided as in the smaller breakers, but it is of increased size. This piston-type air booster is an integral part of the contact structure, and its effectiveness in maintaining short interrupting times during light-current inter-

ruptions can be seen in Figure 6, where a maximum of $4\frac{1}{2}$ cycles for any value of short-circuit current is shown.

Test Data

Many extended series of interruption tests were made in the development of this breaker to obtain optimum co-ordination between the interleaving arc-path length, fin spacing, magnetic-field strength, and air-booster size. Table I shows a series of interruption tests taken on a production breaker, ranging from transformer magnetizing current values to values well above the interrupting rating of 250,000 kva. In no case did the total breaker operating time from trip impulse to interruption exceed 4.5 cycles. These tests were followed by several trip-free closing operations and several two-unit operation duty-cycle tests. The solenoid mechanism, designed for high closing speeds, practically eliminated arcing on closing operations. Figure 7a shows the magnetic oscillogram, and Figure 7b shows the cathode-ray oscillogram of a typical interruption test slightly above the 250,000-kva interrupting rating (test 51). The magnetic oscillogram shows the marked reduction in the short-circuit currents of each of the three phases as

Figure 6. Interrupting time versus current of 15,000-volt Magne-Blast circuit breaker—rated 250,000 kva

1. Interrupting time with air boosters
2. Interrupting time without air boosters

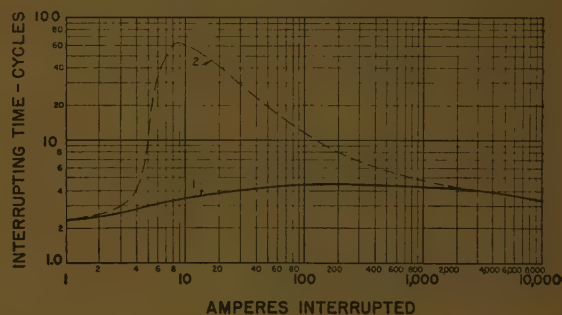
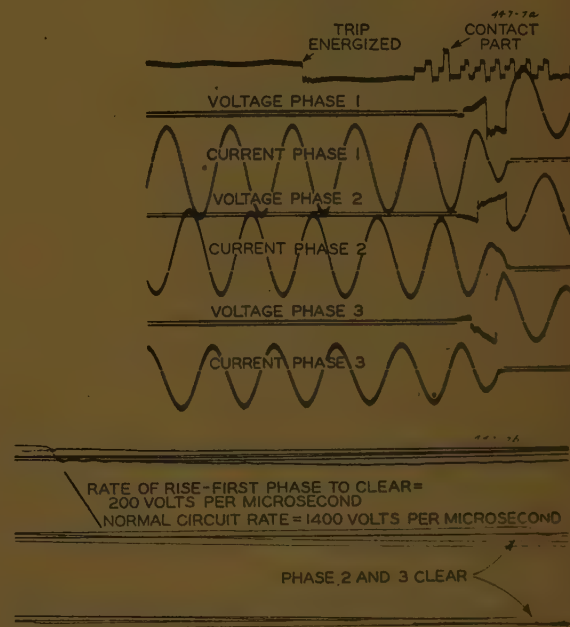


Figure 7

- (a). Magnetic oscillogram of three-phase interrupting test at 270,000-kva, 14,500 volts. Test 51 of Table I. Note marked reduction of current due to arc resistance prior to interruption

- (b). Cathode-ray oscillogram of recovery voltages across each pole following interruption of three-phase test shown in Figure 7a. Rate of rise is reduced from 1,400 volts per microsecond normal for this circuit to 200 volts per microsecond



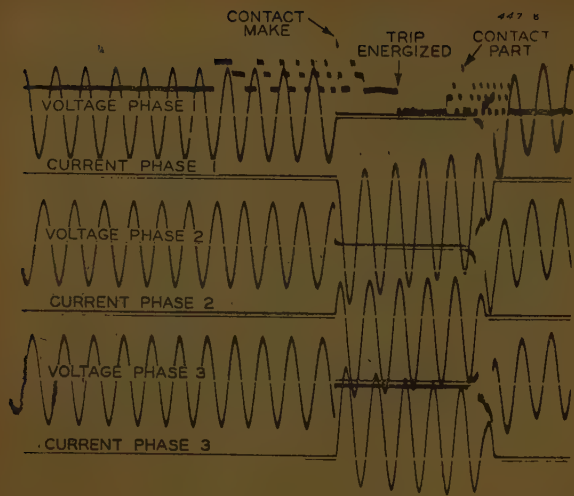


Figure 8. Magnetic oscillogram of three-phase trip-free closing-opening test at 310,000 kva 14,500 volts

Test 64b, Table I (second operation of two-unit operation duty cycle—15-second re-closing

be extended beyond the range originally contemplated for this type of interrupter, as to both voltage and interrupting ability. The magnetic blasting of an arc into an interleaving chute can be controlled to cool and lengthen this arc at a rate necessary to interrupt the currents of a 250,000-kva rating at 15 kv. The proper co-ordination between arc-chute geometry, magnetic-field distri-

the arc resistance increases. The normal circuit rate of rise of the recovery voltage of the first phase to clear on this circuit is 1,400 volts per microsecond. The resistance of the continuous interleaving hot gas path plus the advancement of the phase position of the current from the crest voltage point reduced the rate of rise of recovery voltage from the normal value of 1,400 volts per microsecond to approximately 200 volts per microsecond.

Figure 9 shows the oscillogram of a typical trip-free closing-opening operation at 310,000 kva. This is the second of a two-unit operation 15-second duty-cycle test 64b. These tests demonstrate the ample margin of safety of this breaker for application on 11,000- to 15,000-volt circuits requiring interrupting ratings up to 250,000 kva.

During an extended test series this breaker has demonstrated acceptable factors in reliability and in life. Exhaustive interruption tests have been but a portion of the complete test program. Tests for mechanical and load operations have established its operating life beyond 50,000 operations without the replacement of parts. Insulation tests meet all requirements. Since it was realized that arc-furnace applications rep-

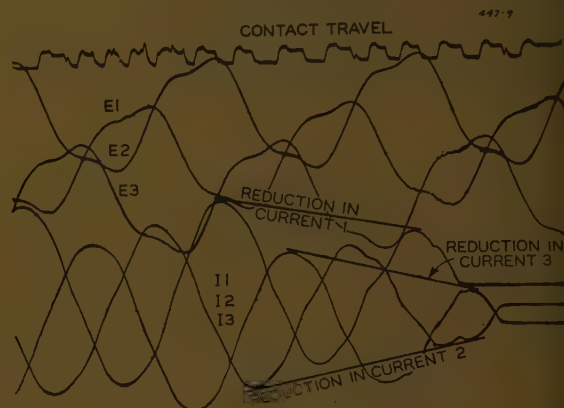
Figure 9. Magnetic oscillogram of three-phase opening test interrupting load current on high side of 6,000-kva 13,200-volt three-phase transformer supplying arc furnace

Note marked reduction of currents prior to interruption

resent a severe service duty, this breaker was placed temporarily on such service in a steel mill during its development. Complete field test equipment, with this temporary installation, provided a qualitative and quantitative analysis of breaker performance for such applications. The oscillograms taken during this investigation demonstrated the value of this type of an interrupter in controlling the rate of rise of recovery voltage when interrupting both the load currents and magnetizing currents of an arc-furnace circuit. Figure 9 shows the reduction in current prior to interruption of the breaker interrupting load current of a 13,200-volt 6,000-kva three-phase transformer supplying an arc furnace.

Conclusions

The established principles of the Magne-Blast-type circuit breaker can



bution and strength, and contact opening speed is used to create arc resistance at a rate most effective in completing efficient circuit interruption. The energy liberated by the arc is absorbed with a minimum of deterioration.

The advantages of the long electrical life of this breaker are combined with a sturdy mechanical design that insures reliability of service with a minimum of care and maintenance.

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Calculation of Unbalanced Voltage Drops in Distribution Circuits With Particular Reference to Multi-grounded Neutrals

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REWARD economic conditions necessitated the use of increasingly precise engineering technique in the design of electric distribution systems. Present wartime demands for conservation of materials have intensified the need for such technique. Control of voltage regulation is a factor of major importance in determining the capital investment in conductors and accessory materials needed for distribution circuits. However, an important hindrance to the application of accurate engineering in taking account of this factor has been the lack of a simple method of calculating voltage drops in circuits having unbalanced conductor impedances and unbalanced loads. The method of symmetrical components, used mainly for calculation of unbalanced fault currents and for solution of a wide variety of problems involving circuit unbalances, has not been accepted generally as a sufficiently rapid method for the solution of voltage-drop problems commonly encountered in distribution-engineering work. Furthermore, simple methods ordinarily used, which neglect unbalanced conditions, often give totally inaccurate and misleading results.

This paper presents the elements of a simplified method applicable particularly to circuits, such as those having multi-grounded neutrals, in which phase-to-neutral mutual impedances differ ma-

terially from phase-to-phase mutual impedances, but in which the spacings in each of the two groups do not differ greatly from each other. This method provides for the combination of the effects of self- and mutual-impedances, so that calculation of voltage drops is reduced basically to a single vector multiplication of a current and an impedance for each phase conductor, and for the earth-neutral combination treated as a single conductor. The change in circuit voltage produced by these drops then can be determined by vector additions and subtractions.

In practical application the entire process is reduced to simple algebra by use of the familiar method of approximation in which the expression $(IX \sin q + IR \cos q)$ is used to represent the arithmetical change in voltage at the load due to drop along the conductors. In this expression, all quantities are scalar, I representing load current, X representing conductor reactance, R representing conductor resistance, and q representing the angle between load current and the particular

circuit voltage under consideration at the receiving end.

Algebraic working equations may be written for various commonly encountered circuit conditions, using as a basis the vector equations developed in this paper. In combination with working impedance data prepared in accordance with the relations shown in the paper, such algebraic equations may be used for the rapid determination of delivered voltage in distribution circuits involving any type and size of conductor.

Fundamental vector equations are developed in the following, and examples of working algebraic equations and working impedance data are given.

General Equations

With reference to Figure 1, which symbolizes a four-wire three-phase circuit with multigrounded neutral, the voltage drop V_A in the circuit composed of conductor A and earth return corresponds to the vector difference between source voltage E_A and load voltage E_A' , as measured to an equivalent earth return plane of reference. The voltage drop V_A is a quantity not obtainable by direct practical measurement but is employed as a basis for writing expressions for general equations. Equations for V_A and for the voltage drops in other conductors can be written as follows:

$$V_A = E_A - E_A' = L(I_A Z_{AA} + I_B Z_{AB} + I_C Z_{AC} + I_N Z_{AN}) \text{ volts} \quad (1)$$

$$V_B = E_B - E_B' = L(I_A Z_{AB} + I_B Z_{BB} + I_C Z_{BC} + I_N Z_{BN}) \quad (2)$$

$$V_C = E_C - E_C' = L(I_A Z_{AC} + I_B Z_{BC} + I_C Z_{CC} + I_N Z_{CN}) \quad (3)$$

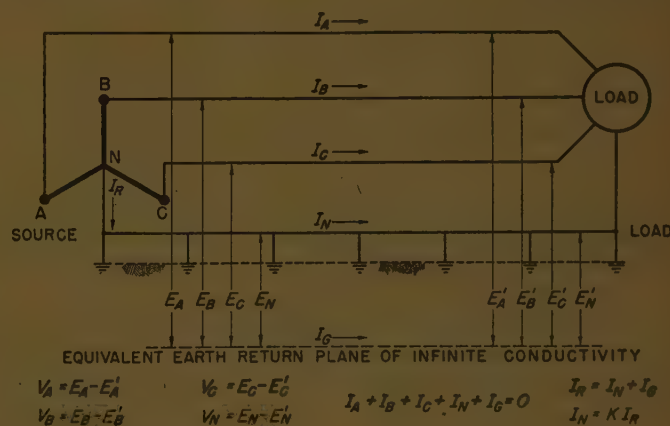


Figure 1. Three-phase four-wire circuit with multi-grounded neutral

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$$V_N = E_N - E_N' = L(I_A Z_{AN} + I_B Z_{BN} + I_C Z_{CN} + I_N Z_{NN}) \quad (4)$$

$$I_A + I_B + I_C + I_N + I_G = 0 \quad (5)$$

where bold-face characters indicate vector quantities, and

I_A , I_B , and I_C = currents in conductors A , B , and C , respectively, in amperes

I_N and I_G = averaged currents in the neutral conductor and in the earth, respectively, in amperes

Z_{AA} , Z_{BB} , Z_{CC} , and Z_{NN} = self-impedances of conductors A , B , C , and N , respectively, with earth return, in ohms per mile

Z_{AB} , Z_{AC} , and so forth = mutual impedances between conductors A and B , and conductors A and C , and so forth, with earth return, respectively, in ohms per mile

Z_{AN} , and so forth = mutual impedance between conductor A and the neutral conductor N , with earth return, and so forth, in ohms per mile

L = length of circuit in miles

Voltage Drop Phase-to-Phase

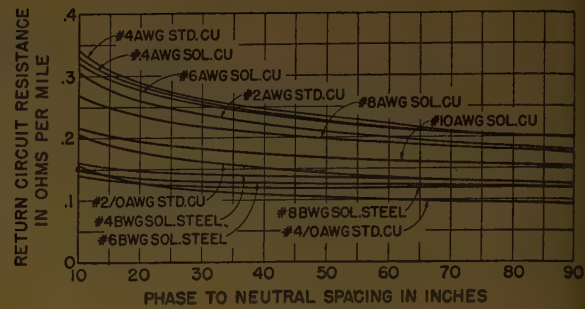
$$V_{AB} = V_A - V_B = I_A(Z_{AA} - Z_{AB})L - I_B(Z_{BB} - Z_{BA})L + I_C(Z_{AC} - Z_{BC})L + I_N(Z_{AN} - Z_{BN})L \text{ volts} \quad (6)$$

Equation 6, for calculating phase-to-phase voltage drops under any condition of unbalanced impedances, contains a term with a multiplier I_N , namely $I_N \times (Z_{AN} - Z_{BN})L$. In this form the equation is not directly usable for a circuit having multigrounded neutral, because the value of I_N is not readily obtainable. However, if it is assumed that phase-to-neutral spacings are equal, the term in question disappears, because the impedance quantities within the bracket then are equal to each other. The quantities $(Z_{AA} - Z_{AB})$, $(Z_{BB} - Z_{BA})$, and so forth, represent positive-phase-sequence impedances as published in handbook tables and can be represented more simply by the symbols Z_A^B , Z_B^A , and so forth, indicating positive-phase-sequence impedance of conductor A at spacing AB , positive-phase-sequence impedance of conductor B at spacing BA , and so forth. Equation 6 may be reduced then to

$$V_{AB} = I_A Z_A^B L - I_B Z_B^A L + I_C (Z_C^B - Z_C^A) L \text{ volts} \quad (7)$$

This equation is applicable to the calculation of phase-to-phase voltage drops in circuits having multigrounded neutrals in which phase-to-neutral spacings are equal. It also is applicable to calculation of phase-to-phase voltage drops in circuits having ungrounded or ungrounded neutrals in which phase-to-neutral spacings are equal. If these

Figure 2. Return-circuit resistance for multigrounded circuits with zero-resistance grounds



spacings are unequal, the resulting error in assuming phase-to-neutral spacings equal to the "geometric mean" will be negligible, unless conductors are large in size and phase-to-neutral spacings differ greatly. All equations in this paper for circuits involving multigrounded neutrals are dependent on the foregoing simplifying assumption, since the improvement in accuracy is not deemed to justify the complexity of rigorous calculations involving unequal phase-to-neutral spacings. This is particularly true, since the type of conductor arrangement usually encountered in connection with circuits having multigrounded neutrals is that in which the neutral position is some distance below and centered under the phase conductors. In such arrangements the proportional differences between individual line-to-neutral spacings usually are very small. If phase-to-phase spacings are assumed equal, the last term of equation 7 disappears, and the calculation reduces to a single vector product for each conductor.

Voltage Drop Phase-to-Neutral

$$V_{AN} = V_A - V_N = I_A(Z_{AA} - Z_{AN})L - I_N(Z_{NN} - Z_{AN})L + I_B(Z_{AB} - Z_{BN})L + I_C(Z_{AC} - Z_{CN})L \quad (8)$$

This may be reduced, if single symbols are used to represent positive-phase-sequence impedance, to

$$V_{AN} = I_A Z_A^N L - I_N Z_N^A L + I_B (Z_B^N - Z_B^A) L + I_C (Z_C^N - Z_C^A) L \quad (9)$$

This equation gives a general expression for voltage drops in multigrounded circuits but is not directly usable in this form, since the term I_N represents only a portion of the residual load current, and its value has yet to be determined. Furthermore, it must be kept in mind, in the application of formulas for this case, that the term I_N is defined as the averaged current in the neutral conductor, and that the mutual-impedance terms are defined similarly. These definitions have been chosen to simplify the development of equations suitable for practical use.

Further assumptions also may be made for simplification of equations with-

out much sacrifice in accuracy. These assumptions are:

- Uniform resistance of grounding electrodes, taken as an average of the resistance of individual grounds.
- Uniform spacing between grounding electrodes along the line, taken as an average of actual spacings.
- Uniform resistivity of the earth.
- Symmetrical arrangement of phase conductors with respect to the neutral conductor. (In cases where this symmetry does not exist, the simplification using geometric mean spacing gives negligible error, unless the three phase-to-neutral spacings are widely different, and conductors are large.)

If these assumptions are used, an equation for I_N in terms of I_R and various calculable impedances has been derived from data developed by the Joint Subcommittee on Development and Research, Edison Electric Institute and Bell Telephone System.¹ The derived equation may be written as follows:

$$I_N = \frac{Z_{AN}}{Z_{NN}} \left(\frac{Z_{NN} - Z_{AN} u}{Z_{NN} - Z_{AN}} \right) I_R = K I_R \quad (10)$$

where

$I_R = I_N + I_G$ = total residual current in amperes, equal to the total return circuit current in the parallel path of the neutral conductor and earth. This current is a fixed vector value for a given condition of loading

I_N = averaged current in the neutral conductor in amperes (as previously defined) and is also fixed for given circuit and loading conditions

I_G = averaged current in the earth in amperes and is fixed for given circuit and loading conditions

u = a factor which takes into account the number and average resistance of the grounding electrodes installed along the line and the terminal grounding conditions. Its value is as follows for a circuit with neutral conductor connected at the source end to a station ground of zero ohm resistance and grounded along its length by grounds of finite resistance, the load being connected at the end of the circuit:

$$u = 1 - \left(\frac{Z_{AN} - Z_{NN}}{Z_{AN}} \right)^2 \frac{1}{\Theta L} \tanh(\Theta L)$$

($u = 1$ for zero-resistance grounds)

$$R_g = \frac{\sqrt{Z_{NN}}}{R_g}$$

R_g = averaged resistance of the grounding electrodes divided by the average number of grounds per mile

Z_{AN} = mutual impedance between conductor A and the neutral, with earth return, in ohms per mile

Z_{NN} = self-impedance of the neutral conductor, with earth return, in ohms per mile

L = length of line from source to load in miles

$$K = \frac{Z_{AN}(Z_{NN} - Z_{AN}u)}{Z_{NN}(Z_{NN} - Z_{AN})}$$

$K=1$ for ungrounded or ungrounded neutral)

If the expression KI_R is substituted in equation 9 for I_N , and if the general superscript NP is used for the line-to-neutral spacing, equation 9 may be written as follows for a multigrounded circuit:

$$V_{AN} = I_A Z_A^{NP} L - I_R Z_N^{NP} K L + I_B (Z_B^{NP} - Z_B^A) L + I_C (Z_C^{NP} - Z_C^A) L \quad \text{volts (11)}$$

This is a general equation for calculating phase-to-neutral voltage drops in any three-phase four-wire multigrounded circuit in which line-to-neutral spacings can be assumed equal, or where these spacings are taken as the geometric mean phase-to-neutral spacings. It applies to lines involving any size or kind of wire for any of the phase or neutral conductors, and to those involving finite resistances of grounding electrodes. It also applies for circuits involving zero-resistance grounds, or ungrounded or ungrounded neutrals, if the values of u and K are determined correctly.

When phase-to-phase spacings are assumed to be equal, in addition to the assumption of equal phase-to-neutral spacings, an expression for phase-to-neutral voltage drops in multigrounded circuits may be developed, as follows:

If the expression $\frac{Z_{AN}(Z_{NN} - Z_{AN}u)}{Z_{NN}(Z_{NN} - Z_{AN})} I_R$ is substituted for I_N or

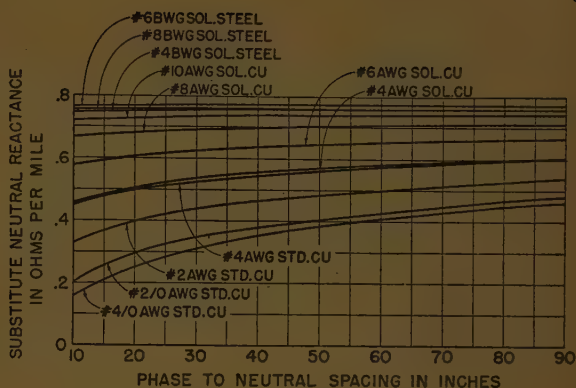
equation 8 may be written

$$V_{AN} = I_A (Z_{AA} - Z_{AN}) L - \frac{Z_{AN}(Z_{NN} - Z_{AN}u)}{Z_{NN}(Z_{NN} - Z_{AN})} (Z_{NN} - Z_{AN}) I_R L + I_B (Z_{AB} - Z_{BN}) L + I_C (Z_{AC} - Z_{CN}) L$$

When the terms are cancelled, this equation may be reduced to

$$V_{AN} = I_A (Z_{AA} - Z_{AN}) L - \left(Z_{AN} - \frac{Z_{AN}^2 u}{Z_{NN}} \right) I_R L + I_B (Z_{AB} - Z_{BN}) L + I_C (Z_{AC} - Z_{CN}) L \quad (12)$$

Figure 3. Substitute neutral reactance for multigrounded circuits with zero-resistance grounds



Since phase-to-neutral spacings are assumed to be equal, and phase-to-phase spacings also are assumed to be equal, the terms $(Z_{AB} - Z_{BN})$ and $(Z_{AC} - Z_{CN})$ are equal to each other and also equal to $(Z_{AB} - Z_{AN})$.

If this expression is substituted subscripts and superscripts are changed, and $I_B Z_{AA} L$ and $I_C Z_{AA} L$ are added and subtracted, equation 12 becomes

$$V_{AN} = I_A Z_A^{NP} L - \left(Z_{PN} - \frac{Z_{PN}^2 u}{Z_{NN}} \right) I_R L + (I_B + I_C) (Z_A^{NP} - Z_A^P) L \quad (13)$$

Since

$$I_A + I_B + I_C + I_N + I_G = 0$$

and

$$I_N + I_G = I_R$$

$$I_A + I_B + I_C = -I_R$$

and

$$I_B + I_C = -(I_A + I_R)$$

Substituting

$$-(I_A + I_R)$$

for

$$(I_B + I_C)$$

equation 13 reduces to

$$V_{AN} = I_A (Z_A^{NP} + Z_A^P - Z_A^{NP}) L - I_R \left[\left(Z_{PN} - \frac{Z_{PN}^2 u}{Z_{NN}} \right) + Z_A^{NP} - Z_A^P \right] L$$

$$V_{AN} = I_A Z_A^P L - I_R \left[\left(Z_{PN} - \frac{Z_{PN}^2 u}{Z_{NN}} \right) + Z_A^{NP} - Z_A^P \right] L$$

or

$$V_{AN} = I_A Z_A^P L - I_R \left[\left(Z_{AA} - \frac{Z_{PN}^2 u}{Z_{NN}} \right) - Z_A^P \right] L \quad (14)$$

A convenient name for the bracketed expression in the preceding equation is "substitute neutral impedance," and it

may be represented by the symbol Z_{SN} as follows:

$$V_{AN} = I_A Z_A^P L - I_R Z_{SN} L \quad \text{volts} \quad (15)$$

Similarly

$$V_{BN} = I_B Z_B^P L - I_R Z_{SN} L$$

and

$$V_{CN} = I_C Z_C^P L - I_R Z_{SN} L$$

Thus, by using two simplifying assumptions, namely, phase-to-phase spacings are equal, and phase-to-neutral spacings are equal, the calculation of phase-to-neutral voltage drop reduces to a simple vector multiplication of a current and an impedance for the phase conductor and a current and impedance for the return parallel path composed of neutral and earth.

Equation 15 may be used to calculate voltage drops in single-phase and in open-wye circuits in addition to three-phase circuits for which the equation is developed.

Reduction to Algebraic Approximations

As examples of reduction of these equations to algebraic working form by the method of approximation mentioned in the introduction, formulas for line-to-neutral voltage change in a three-

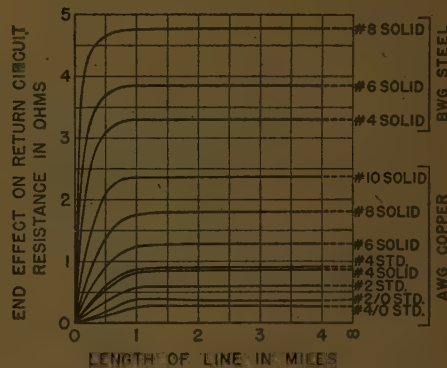


Figure 4. End effect on return-circuit resistance with finite-resistance grounds

$$R_g = 1$$

phase four-wire circuit with multi-grounded neutral having a single-phase load connected from line *A* to neutral, phase sequence being *A, B, C*, may be written as follows:

Voltage reduction at load, phase *A* to neutral, is very nearly

$$I_A \cos \phi (R_A + R_R) + I_A \sin \phi (X_A^P + X_{SN})$$

Voltage increase, phase *B* to neutral, is very nearly

$$I_A R_R \cos (60^\circ + \phi) + I_A X_{SN} \sin (60^\circ + \phi)$$

Voltage increase, phase *C* to neutral, is very nearly

$$I_A R_R \cos (60^\circ - \phi) - I_A X_{SN} \sin (60^\circ - \phi)$$

In these expressions all quantities are scalar and

R_A = total resistance of conductor *A*

R_R = total return circuit resistance, or resistance of earth-neutral combination

X_A^P = total handbook reactance of conductor *A* at phase-to-phase spacing

X_{SN} = total substitute neutral reactance of the circuit

ϕ = power-factor phase angle of the load current with respect to load voltage

Substitute Neutral Impedance

The bracketed expression for Z_{SN} in equation 14 can be reduced to the form

$$Z_{SN} = Z_{AP} - \frac{Z_{AN}^2}{Z_{NN}} + \frac{(Z_{NN} - Z_{AN})^2}{Z_{NN} \theta L} \tanh (\theta L) \quad (16)$$

In this expression, if resistance of connections to ground is assumed equal to zero, θ becomes infinite, and the term $(Z_{NN} - Z_{AN})^2 / (Z_{NN} \theta L) \tanh (\theta L)$ disappears. The first two terms, therefore, represent conditions under which the division of current between neutral and earth is determined only by self- and mutual impedances of phase and neutral conductors and the resistivity of the earth itself. Such conditions exist approximately in the central portions of long untapped circuits with multi-grounded neutrals. The last term represents conditions at the load end of the circuit, where the escape of current from neutral to earth is retarded by resistance of ground connections, zero-resistance

grounding conditions at the source and being assumed in the derivation of the equation in this particular form. For convenience, the last term of equation 16 is called "end effect." It is greater, the higher the resistance of ground connections. If grounding conditions are no better at the source end of the circuit than along its length, then an additional end effect must be inserted for the source end, doubling the value of the last term. If the load is not located at the end of the circuit, then two end effects in parallel relation must be taken into account, since current will flow in the neutral in both directions from the load.

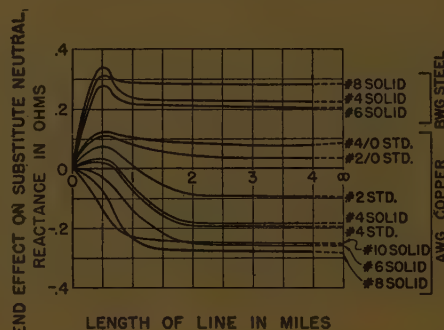


Figure 5. End effect on substitute neutral reactance with finite-resistance grounds

$$R_G = 1$$

It has been customary in calculation of fault currents by the method of symmetrical components to neglect end effects and make calculations under the assumption that ground connections have zero resistance. This often results in negligible error, especially in the case of long circuits, such as transmission lines. However, in the case of voltage-drop calculations in distribution circuits, omission of end effects frequently will result in large error.

For use in practical engineering work, end effects and the other component of Z_{SN} composed of the first two terms of the expression in equation 16 can be calculated to cover a typical range of conductor types and sizes and incorporated in tabular or chart form, for example, as shown in Figures 2, 3, 4, and 5. Figures 2 and 3 give return circuit resistance and substitute neutral reactance for the first two terms of the expression,

respectively, for various conductor types, sizes, and spacings. Figures 4 and 5 give resistance and reactance end effects for various conductors but for a particular value of R_G or resistance of ground connection per mile. A series of such charts for various values of R_G has been prepared as working data for practical application of the method.

In Figures 4 and 5 the last term of equation 16 has been multiplied by L and total values are read directly opposite circuit lengths. In Figures 2 and 3 the values are unit values per mile and must be multiplied by the length of circuit before substitution in working formulas.

For the construction of the charts of Figures 2, 3, 4, and 5, the following physical constants were used as reasonably typical of conditions likely to be met in practice:

Earth resistivity.....50 meter ohms
Distance from conductors to image....2,000 feet
Conductor temperature.....65 degrees centigrade
Frequency.....60 cycles
Phase-to-phase spacing.....40 inches
(Deviations from this value ordinarily encountered have relatively little effect on accuracy)
Steel conductors.....high-tensile strength
Current intensity.....10 amperes per conductor

Circuits With Ungrounded Neutrals

The foregoing material has been confined to circuits with multigrounded neutrals, but the method is applicable to circuits with ungrounded or ungrounded neutrals by suitable modification of the expression for Z_{SN} . For such circuits this is found to be

$$Z_{SN} = (Z_{N^P} + Z_{A^P} - Z_A^P) \quad (17)$$

These are all positive-phase-sequence impedances readily obtainable from handbook tables.

Reference

1. ENGINEERING REPORTS, volume IV, Joint Subcommittee on Development and Research, Edison Electric Institute, Bell Telephone System. Engineering report 37, COMPUTATION OF ZERO-SEQUENCE IMPEDANCES OF POWER LINES AND CABLES. Page 314, equations 1-3.

Overloading of Transformers—Cases Not Covered by the General Rules

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Synopsis: The general relations covering the heating of transformers and the effects of this heating on safe overloads are simple in principle, but the mathematics involved are complex. When suitable curves are used to express the relations, the simplicity is evident. Loading of transformers and other equipment by temperature is increasingly common and rightly so. An understanding of the principles involved aids in intelligent application of information for loading by temperature. The usefulness of the American Standard C57.3, "Guides for Operation of Transformers and Regulators," 1942 would be increased by the inclusion of temperature-time charts so that a solution may be obtained for the unusual loading case. These charts are based on the same principles on which the present rules are based. In addition to simplifying the procedure for taking care of special cases, such charts present a graphic picture of the heating relations of transformers.

THE American Standard "Guides for Operation of Transformers and Regulators" C57.3, 1942 and the interim reports on overloading (references 21

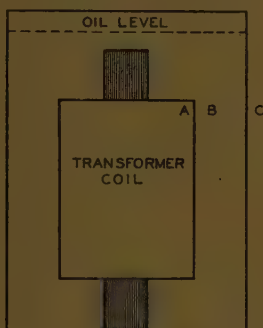


Figure 1. Oil-immersed transformer

and 24) give information which covers many of the overloading conditions encountered with transformers. These rules, however, do not cover every situation. In order to help fill this lack, charts have been prepared which will enable the safety of practically any special case of loading to be determined.

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In addition to such quantitative values, there is also a need for a qualitative summation of the general principles on which transformer loading is based. Such a summation will aid in correct application of the rules and result in confidence that the application is correct. The general principles are outlined after which their application to specific cases is demonstrated by the use of charts.

General Principles

A familiar operation like heating water on a stove includes all the elements involved in heating and cooling of transformers. When a teakettle of cold water is placed on a stove, the water heats slowly because of its high thermal capacity. The heat given off by the hot gases of the fire must be transmitted to the water, which absorbs heat and increases its temperature. At all times, the temperature of the fire is higher than the temperature of the water, and heat flows from the fire to the water.

After the teakettle is removed from the fire the water remains hot for a considerable time. During this period, its temperature gradually decreases as the water loses heat to the surrounding air.

In a transformer, heat is generated in the copper of the windings and in the iron core. The transformer starting cold, a portion of this heat is absorbed by the copper because of its thermal capacity, and a portion of the heat is transferred to the oil. The oil, in turn, absorbs heat because of its thermal capacity, and, after its temperature increases, dissipates heat to the cooling medium, usually the air sur-

rounding the transformer. In Figure 1 the flow of heat is from the copper at A to the oil at B and, in turn, from the oil at B to the air at C. The temperature difference between the copper at A and the adjacent oil at B is commonly called the copper "gradient." The difference in temperature between the oil at B and the air at C is commonly called the "oil rise" in temperature. If A is the copper adjacent to the hottest oil B, the copper temperature of A will be the hot-spot copper temperature, and the temperature difference between A and B will be hot-spot copper gradient. Since the temperature of the hottest spot of the copper is the temperature which controls permissible loading, the charts used in this paper are the charts of hot-spot temperature.

The rate at which insulation deteriorates depends upon the temperature, an increased temperature causing an increased rate of insulation deterioration. It is assumed that continuous temperature of 95 degrees centigrade hot-spot temperature of the copper will result in satisfactory length of life for a transformer. If the operating temperature is below 95 degrees centigrade for part of the time, it can be allowed to be above 95 degrees centigrade for part of the time and still secure the same transformer life. If advantage of this fact is taken, higher loads and higher temperatures can be permitted for short periods of operation. If the transformer is cool when the overload is applied, advantage may be taken of the thermal capacity of the transformer material, and higher overloads with a corresponding higher rate of heat generation can be permitted when the transformer is cool than when it is hot.

Heating and Cooling Curves

Quantitative variations of transformer temperatures with time can be shown conveniently on curves such as Figure 2. The rate of temperature rise with time depends upon the load upon the transformer.

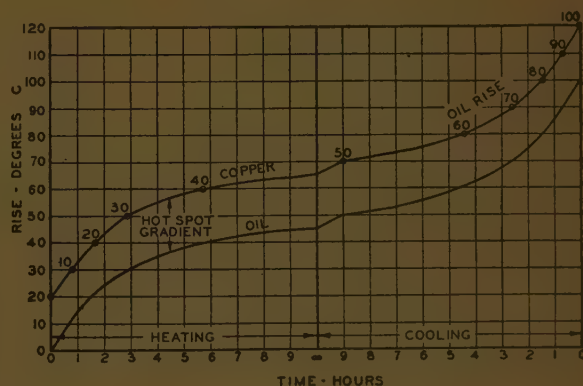


Figure 2. Heating and cooling curves for a typical power transformer carrying full load

Rises shown are hot-spot copper and top oil rise above ambient air temperature

The curves of Figure 2 have been drawn for 100 per cent load. The left-hand part of the oil curve of Figure 2 shows how the temperature of the oil increases with time as load is applied to the transformer starting cold. The right-hand part of the oil curve shows the manner in which the oil temperature decreases when the starting temperature is higher than the final temperature of the oil. Figure 2 is really two sets of curves in one, the left-hand side of the chart being the curves for increasing copper and oil temperature and the right-hand side of the chart being the curves of decreasing copper and oil temperature. The side of the chart to be used is not determined arbitrarily but is determined by the oil-temperature rise. If the oil rise is above 45 degrees centigrade at the start of the period of time considered, the starting temperature and, consequently, the starting time will fall on the right-hand side of the chart. For example, if the starting oil-temperature rise were 55 degrees centigrade, the starting time would be six hours on the cooling or right-hand side of the chart. If, however, the starting oil-temperature rise were 35 degrees centigrade, the starting time would be four hours on the left-hand side of the chart. In either case, as time elapses the numerical value of the time in hours would increase.

As shown by the left-hand side of Figure 2, when a cold transformer is loaded, the oil temperature rises rapidly almost as a straight line because practically all of the heat generated is absorbed by the copper and iron and oil of the transformer. If no heat-dissipating surface were supplied, the temperature would increase in a straight line indefinitely until failure occurred. After a time the curve of oil-temperature rise departs from a straight line as more heat is dissipated to the surrounding air. After several hours the rate of increase in temperature is very slow, until finally all of the heat generated is being dissipated to the air and the oil temperature no longer increases.

The right-hand side of Figure 2 shows how the oil temperature decreases with time when the ultimate temperature is lower than the initial temperature. The rate of decrease in temperature is most rapid at the beginning near zero time. The rate of decrease in temperature becomes slower with lapse of time, until the same ultimate temperature is reached as for the same load with rising temperature.

Because the copper-over-oil gradient changes rapidly compared to the rate of change of the oil temperature, the copper temperature is assumed to be a constant amount above the oil temperature for any

load by the value of the gradient of the transformer, and the copper curve is drawn accordingly. If the oil rise of the transformer is known (as by reading the thermometer on the transformer case) and 100 per cent load is applied, the temperature rise from that time on can be determined from the curve by assuming that the starting time is the time corresponding to the starting oil temperature. If, for example, it is assumed that the starting oil temperature is 30 degrees centigrade, the starting time would be 2.8 hours as read from the oil curve corresponding to 30 degrees centigrade. The transformer does not know whether the 30 degrees centigrade was obtained by carrying 100 per cent load starting cold or by cooling down from a higher temperature. Consequently, it may be assumed for purposes of calculation that the 30-degree-centigrade rise was obtained following the 100 per cent load curve, the load being applied when the transformer was cold. If this load of 100 per cent is carried for two hours, the total time will be 2.8 plus 2 = 4.8 hours. The copper temperature rise at the end of 4.8 hours will be 58 degrees centigrade as read on the copper curve. Each point on the copper curve corresponds to a definite oil temperature on the oil-temperature curve. Accordingly, it is possible to dispense with the oil curve and use only the copper curve if the points on the copper curve are labeled with figures as shown in Figure 2.

Accordingly, for an initial oil temperature of 30 degrees centigrade and 100 per cent load, the starting point on the copper curve is the point marked 30, corresponding to a time of 2.8 hours. Two hours later at a time of 4.8, the copper-temperature rise is read as 58 degrees and the corresponding oil temperature can be estimated as 38 degrees by interpolating between the 30- and 40-degree marks on the copper curve, or by subtracting the

known gradient of 20 degrees centigrade. The same general principles apply not only to transformers but also to other types of electrical equipment where thermal characteristics are a factor in determining the safe load which can be carried.

Use of Temperature-Time Chart

Figure 3 consists of curves similar to Figure 2 for 0, 60, 80, 100, 120, 140, 160, 180, and 200 per cent loads for the hot-spot-temperature rise above the ambient air. They were drawn in exactly the same manner as the copper curve of Figure 2. The dotted lines are drawn through points of equal oil temperatures. The oil temperature values are indicated by the figures at each end of the dotted lines.

The purpose of the curves of Figure 3 is not solely to secure a chart by which temperature values can be calculated readily. It has the advantage of presenting the various factors of time, per cent load, and rise in degrees centigrade in such a manner that the physical phenomena may be followed. For example, the curve for 120 per cent load is a curve of the temperature rise of the hot-spot copper above the surrounding air versus time when a transformer is carrying 120 per cent load. The dotted lines merely represent a simple means of indicating the oil temperature on each curve corresponding to the given copper temperature. As stated, the purpose of the chart is not only to determine temperature values for given load cycles but also to present a physical picture of the rise and fall of the temperature during the load cycle.

EXAMPLE

If the initial oil-temperature rise is 30 degrees centigrade, what will the temperature be at the end of the time

Figure 3. Heating and cooling curves for a typical transformer for various loads for the following full-load values:

Hot-spot gradient, 20 degrees centigrade; oil rise, 45 degrees centigrade; ratio of copper loss to iron loss, two; thermal time constant, three hours. Rises shown are hot-spot copper and top oil rise above ambient-air temperature

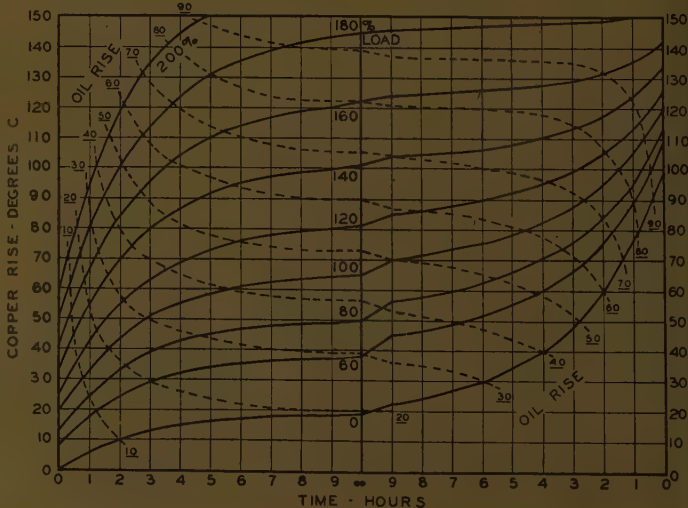


Table I

Per Cent Load	Time (Hours)	Start-Elapsed	Final	Final Hot-Spot Copper Rise	Final Copper Temperature With 10 Degrees Centigrade Ambient
100	2	2.8	4.8	58	68
140	1	2.2	3.2	82	92
80	1	6.6	7.6	58	68

When 100 per cent load is carried for two hours followed by 140 per cent load for one hour followed by 80 per cent load for one hour? Is this a safe loading condition where the ambient temperature is 70 degrees centigrade?

In Figure 3, the time corresponding to 30-degree-centigrade oil rise on the 100 per cent load curve is 2.8 hours; 2.8 hours plus two hours equals 4.8 hours. The copper-temperature rise corresponding to 4.8 hours on the 100 per cent load curve is 58 degrees centigrade. Moving to the 140 per cent load curve, keeping parallel to the dotted lines, one determines the time of 2.2 hours as being the starting time corresponding to the same oil-temperature rise (38 degrees centigrade) as for the finish of the preceding run; 2.2 hours plus one hour equals 3.2 hours. The copper-temperature rise corresponding to 3.2 hours on the 140 per cent load curve is 82 degrees centigrade which is the copper-temperature rise at the end of that time. Again moving parallel to the dotted lines, one finds the starting time for the 80 per cent load curve to be 6.6 hours. Adding 6.6 hours plus one hour equals 7.6 hours. The copper-temperature rise corresponding to 7.6 hours on the 80 per cent load curve is 58 degrees centigrade. By interpolation between the dotted curves, this corresponds to a 44-degree-centigrade oil temperature. For convenience in calculation, these values are arranged in Table I.

Since the hot-spot (copper) temperature is below 95 degrees centigrade at all times, it is obvious that the loads described in Table I may be carried with safety.

Any load cycle can be traced through the curves in similar manner, and the oil and copper temperature at any point on the cycle may be readily determined. In addition, at any point on the cycle the effect of increased time may be determined, since, by inspection, it is obvious whether further increase in time will greatly increase or decrease the rise obtained.

The chart of Figure 3 can, of course, be drawn with other variables plotted on the horizontal and vertical axis, or by means of nomograms or special slide rules. The

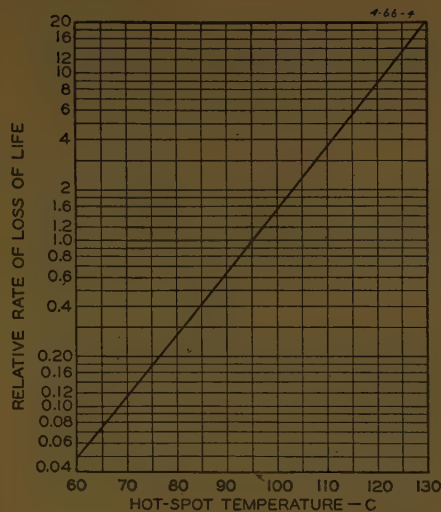


Figure 4. Rate of loss of life of transformer insulation in terms of rate of loss of life at 95 degrees centigrade

arrangement of Figure 3, however, produces a better physical picture for most practical cases.

The curves of Figure 3 have been drawn for the following transformer characteristics at 100 per cent load: a ratio of copper loss to iron loss of two to one, a hot-spot copper gradient above the oil of 20 degrees centigrade, an ultimate oil rise above the ambient air of 45 degrees centigrade, and a thermal time constant of three hours. Many modern power transformers have characteristics which are approximately the same as these assumed values, and the curves of Figure 3 can be used for such transformers.

Some transformers, particularly older transformers, may have higher gradients and shorter time constants than those used to determine the curves of Figure 3. The chart of Figure 5 has been drawn for use on such transformers with lower overload capabilities, assuming the following full-load values: a hot-spot gradient of 30 degrees centigrade, oil rise 35 degrees centigrade, ratio of copper loss to iron loss at

full load 2 to 1, thermal time constant two hours. For general use either the charts of Figure 3 or the chart of Figure 5 will be used, whichever is closer to the characteristics of the actual transformer. In case of doubt Figure 5 should be used.

The use of typical charts and the use of typical values of constants for determining permissible overloads of transformers follow the general principles which are used in preparing other guides for operation of transformers, such as American Standard C-57.3. When this section on the guides for operation of transformers is revised, charts such as Figure 3 or Figure 5 or both would add useful information. If other values than those assumed for Figures 3 and 5 are chosen for the other data, these figures can be revised, using the same constants as are used for the other rules. Detailed means by which curves of Figures 2, 3, and 5 may be obtained are described in reference 20 (see the appendix).

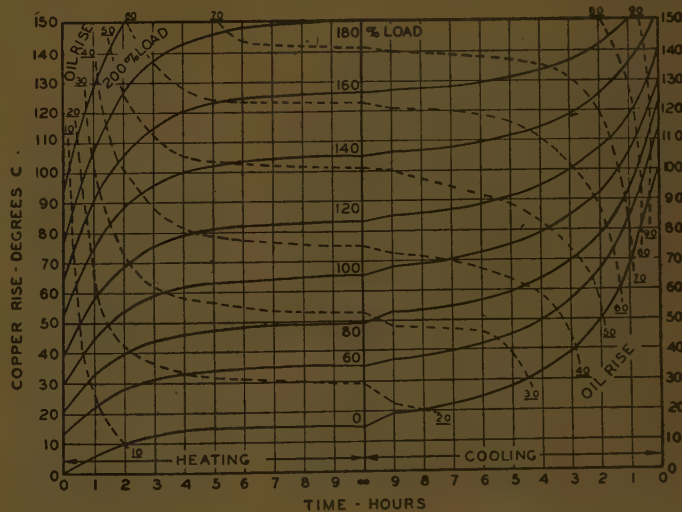
For any particular transformer, values of hot-spot copper gradient and top oil rise at full load, and the thermal time constant (the time which would be required for the transformer oil to reach its ultimate temperature if all the heat were absorbed in the oil and no heat were dissipated to the air) may be obtained from the transformer manufacturer. For more accurate results, of course, charts similar to Figures 3 and 5 may be constructed especially for a particular transformer, but this refinement is seldom necessary.

Calculation of Loss of Life of a Transformer

The curves of Figures 3 and 5 can be used to calculate allowable loads and the loss of life for a given loading cycle. The loss of life for a given loading cycle can be calculated from Figure 4 which shows the loss of life in percentage of the loss of life

Figure 5. Heating and cooling curves for a typical transformer for various loads for the following full-load values:

Hot-spot gradient of 30 degrees centigrade; oil rise, 35 degrees centigrade; ratio of copper loss to iron loss, two; thermal time constant, two hours. Rises shown are hot-spot copper and top oil rise above ambient-air temperature



of a transformer operated continuously with a hot-spot copper temperature of 95 degrees centigrade. For convenience in calculation it may be assumed that the ultimate temperature is maintained for the total time the load remains constant. (If more precise values are desired, the curve of temperature versus time may be drawn.) The comparative loss of life may be determined as shown below. The average rate of loss of life over the period considered is the rate of aging relative to the base rate of continuous operation at 95 degrees centigrade hot-spot temperature.

EXAMPLE

What is the loss of life during the preceding example as compared to the loss of life at 95 degrees centigrade when the following temperatures were obtained:

- 68 degrees centigrade at end of two hours of 100 per cent load
- 92 degrees centigrade at end of one hour of 140 per cent load
- 68 degrees centigrade at end of one hour of 80 per cent load

What is the highest ambient temperature at which this loading could be carried without the average rate exceeding the normal rate of loss of life?

From Figure 4, the rate of loss of life at 68 degrees centigrade is 0.10; and at 92 degrees centigrade, 0.74 times the rate of loss at 95 degrees centigrade.

The average rate =
$$\frac{0.10 \times 2 + 0.74 \times 1 + 0.10 \times 1}{4} = 0.26 \text{ times the rate of loss of life at 95 degrees centigrade}$$

This corresponds to an equivalent temperature from Figure 4 of 79 degrees centigrade for the four-hour period. The ambient temperature was ten degrees centigrade; it could have been 95 degrees centigrade—79 degrees centigrade=16 degrees higher or equal to 26 degrees centigrade before the average rate of loss of life exceeded the normal rate.

Safe Loads for Short Times

Another approximate method which may be used is to compare the final temperatures with those given in the Standards for short-time loading.

The following temperature limits may be used for recurrent loads:

- Two hours or less—110 degrees centigrade
- Eight hours or less—105 degrees centigrade
- 24 hours or less—95 degrees centigrade

Transformer hot-spot copper temperature which is calculated as the sum of the temperature rise from Figure 3, and the ambient temperature should not exceed these values.

If the temperatures obtained during the desired loading do not exceed these values for the times corresponding to the temperature rises on the curve of Figure 3, the loading will be within safe limits. In the preceding example, the copper temperatures given in Table II were obtained with ten degrees centigrade ambient: The temperature limit for 4.8, 3.2, and 7.6 hours is 105 degrees centigrade as shown in the last column of Table II. The final copper temperatures are all below the limit, so consequently the loads may be carried with safety. According to Table II, the ambient temperature could have been equal to 105—92=13 degrees higher or equal to 23 degrees before safe temperatures were exceeded. This approximate value may be compared with the more accurate value of 26 degrees centigrade obtained by the previous method.

Summation

The general principles underlying safe loading of transformers can be conveniently expressed on a quantitative basis by the use of charts. These charts consider the effect of ambient temperature and thermal capacity of the transformer as well as the other physical constants of the transformer. Thermal characteristics of a transformer cannot be precisely determined, but fortunately precise determination is not necessary for practical use. By using assumed values for constants which give results on the safe side (for example, using a gradient for calculation which is not smaller than the actual gradient, using a thermal time constant which is not larger than the actual time constant) one may be certain that the loading obtained is conservative. This follows the general principles in common use for overloading transformers. The heating of other apparatus follows the same laws as the heating of transformers. Similar charts can be prepared using the same principle for the set of constants which apply to the particular apparatus.

Conclusions

1. The fundamental principles involved in transformer heating and overloading are simple and applicable not only to transformers but to other devices which generate internal heat.
2. By using simple charts, the advisability of a contemplated overload cycle for a transformer can be quickly determined. The usefulness of the American Standards would be increased by the inclusion of such charts.
3. Where the more general rules are not applicable to the loading being considered, the heating and loss of life for the loading

can be quickly calculated by the method given.

4. In overloading transformers, the cautions given in the interim report should be observed.

5. If a short-time overload is to be carried on an existing transformer, the starting point in determining the safe time for the load should be the present oil temperature.

Appendix. Description of Curves

The curves of Figures 2, 3, and 5 are curves of heating and cooling versus time and are calculated curves which closely approximate the curves which would be obtained if frequent readings were taken on a transformer in operation, starting with the transformer oil at air temperature for the heating curves and starting with the oil at 100 degrees centigrade rise for the cooling curves. An extensive exposition of the existing relations is given in the references, especially references 2, 5, and 20. The

Table II

Final Time (Hours)	Final Copper Rise	Final Copper Temperature WITH 100 Degrees Centigrade Ambient	Temperature Limit
4.8.....	58.....	68.....	105
3.2.....	82.....	92.....	105
7.6.....	58.....	68.....	105

curves are calculated in accordance with these references. To make the curves more generally useful, the effect of thermal capacity of the copper alone is neglected. This produces appreciable error only for short times on the order of 15 minutes or less, and even there the effect is to increase the safety of loading.

The curves are drawn for the following relations of references 2, 5, and 20:

1. The ultimate hot oil rise over ambient air varies as the 0.8 power of the loss. Consequently, the heat dissipation from the oil to the air varies as the 1.25 power of the temperature.
2. The copper loss varies as the square of the load
3. The hot-spot copper gradient varies as the 1.0 power of the load.
4. The thermal time constant of the copper alone is assumed to be negligible.
5. The thermal time constant of the whole transformer is assumed to be constant at the given value.

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5. EFFECT OF OVERLOADS ON TRANSFORMER LIFE,

The Vibration of Electric Contacts

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IN evaluating an electric switching device, its following characteristics must be considered:

1. Ability to close the circuit without undue deterioration of contacting points.
2. Ability to carry the current without injurious temperature rise.
3. Ability to interrupt the circuit with the least destruction of contacting members.

Considerable attention has been given to the study of the two latter problems,

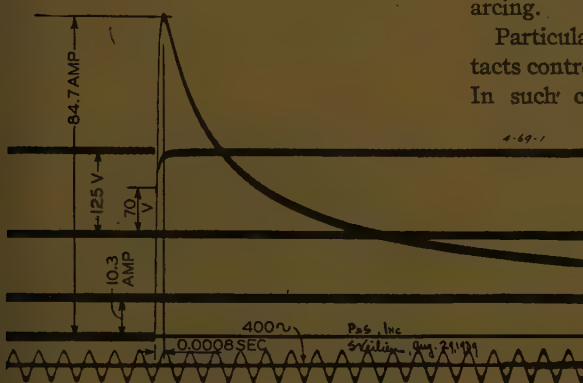


Figure 1. Oscillogram showing current rise in 1,200-watt lamp circuit on 125 volts, direct current

while the "making" of contacts has been practically neglected. However, the engineers interested in the life or in the

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proper operation of switching devices realize that, in many applications, particularly those involving high initial power surges, the "making" of the contacts may be even more important than their "breaking" performance.

A switch, to "make" properly, must bring the contact points into union without their bouncing or vibrating. That is, once touched, the points should not separate, for otherwise the circuit would be momentarily broken with resulting arcing.

Particularly vulnerable are the contacts controlling tungsten filament lamps. In such circuits, because of the high

temperature coefficient of resistivity of the filament material, the initial current is several times that of the normal lamp current. A typical oscillogram, Figure 1, recorded an inrush current of 800 per cent of the normal. Consequently, if vibration of contacts occurs, during their "making" period, the contact points are called upon to interrupt and to "close" a

load eight times their rated capacity. Such excessive current, of course, destroys the contacting parts very rapidly.

Vibrating contacts impose a greater duty on the contacting members. Such contacts are subjected to the load interruption, not only during their "breaking" function, but also while they are "making." Naturally, in circuits producing high current surges, this condition causes very rapid disintegration of contact material and welding. The results of vibrating contacts controlling a circuit of lamps are shown in Figure 2. Specimens 2a were closing and opening a circuit having lamps as load and are showing severe pitting and wear of metal at the center portion of the contact; it was caused by "breaking" the circuit after initial "make." Specimens 2b were controlling a d-c noninductive resistance load and are characterized by deterioration of metal at the wings of the contact; this wear was caused by arcing incident to "breaking" of circuit; it will be observed further that the center portion of the contact was not affected because of absence of high current surges in non-inductive resistance circuit. Life of contacts vibrating during "making" is reduced, and, in some circuits, their use becomes prohibitive.

Similar destructive results occur in switches controlling motors, since the starting current of motors is several times their "running" values.

In the application of contacts involving sending out a predetermined number of impulses (telephony, electric clock systems, supervisory control, and so forth) for selection of indication or of a function of remotely located apparatus, the contacts must be vibrationless, for otherwise

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(a). Switch contacts controlling lamp load circuit



(b). Switch contacts controlling noninductive resistance circuit

Figure 2

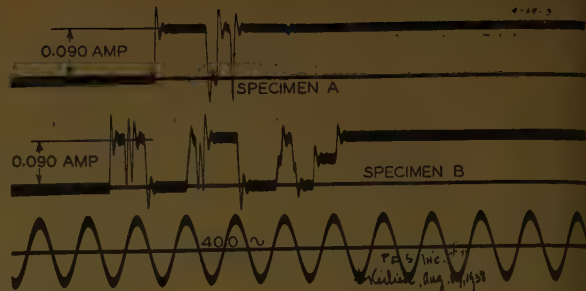
the number of "makes" and "breaks" would not correspond to the assigned code, thus producing erroneous results. While the effect of vibrating contacts may be compensated by the use of slow-acting magnets, such a scheme is not desirable, for it limits the speed of the system.

Functionally the contacts may be divided into two general groups: butting type (contactors, relays, switches, keys, circuit breakers, and so forth) and knife type (knife switches, snap switches, oil switches, circuit breakers, and so forth).

In a switch of elementary design, the blades may produce violent vibration, as indicated in oscillogram Figure 3. Observe several complete circuit interruptions by either specimen. Butting type of contacts, such as used in relays, keys, and so forth, usually close with pronounced bouncing, as shown in Figure 4. Many circuit interruptions took place in relatively lengthy periods of time elapsing between first "make" and final completion of the circuit, in both exposures. Therefore, the matter of vibration suppression becomes an important problem in switching mechanism designs.

Figure 3. Oscillogram showing contact vibration of ordinary snap switch

Snap switches closing noninductive resistance circuit on 125 volts, direct current



For vibrationless operation, it is necessary to prevent contact overtravel at right angles to the direction of movement in case of the knife type of contacts, and to eliminate bouncing in case of butting type. In either case the energy of the moving system in excess of that utilized to unite contacts must be dissipated. Unless this is done, the impact will cause rebound.

For the interruption of d-c circuits, it is generally considered that the contacts must travel with high velocity. However, such a characteristic is objectionable during their "making," for the kinetic energy resulting from this high velocity would be more difficult to absorb.

One of the most common means of contact vibration suppression is to design the stationary contact under spring pressure, so arranged that, when the moving contact strikes the stationary contact, the spring absorbs the energy of the moving system.¹ Similar results may be obtained by the use of a dashpot, which would be put into action on the closing of contacts and thus would act as a damper in absorbing the energy of the movable contact.

Another method of reducing the contact vibration is to use hollow contacting points,² filled with metallic powder. When suddenly arrested by the stationary contact, the powder particles create heat because of friction between them, thus dissipating the energy which would have produced vibration.

The snap switch offered a particularly difficult problem. Because of its limited size and low cost, elaborate means for the absorption of energy could not be incorporated. Consequently, it was necessary to devise some arrange-

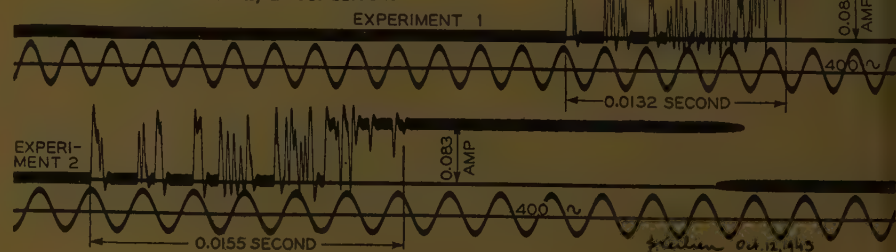
ment to suppress the vibration without external means. The investigation resulted in a contact with self-contained vibration suppressor. This was accomplished by preloading mutually two halves of the flexing contact member. Thus, when the flexing contact arm engaged the stationary member (like a knife switch) the energy, which would have caused vibration, was absorbed by the preloaded contact, without sacrificing high contact velocity.

For the analysis of the factors affecting the "making" of contacts, assume a knife-type snap switch, in which a movable flexing blade engages stationary contacts, completing the circuit. It will be apparent from further discussion that the analysis is applicable to any type of knife contacts. In this switch the movable element (the blade) is brought into rapid motion by a spring which is suddenly released, having been gradually loaded previously by the movement of a manually operable handle. Thus, the operator has no control of the speed with which the contacts engage. The blade collides with the stationary contacts during "making," and this action can be treated as an impact.

Experimental investigations of contact vibration required the study of several pertinent factors. Actual oscillograms, mentioned heretofore, give indications that the oscillations are damped, as expected; the velocity of the moving system is high;³ the mass of the moving system cannot be materially reduced without the detrimental effects of high current density of current-carrying parts,

Figure 4. Oscillogram showing circuit interruptions during "making" of relay contacts

Relay contacts closing noninductive resistance circuit on 125 volts, direct current



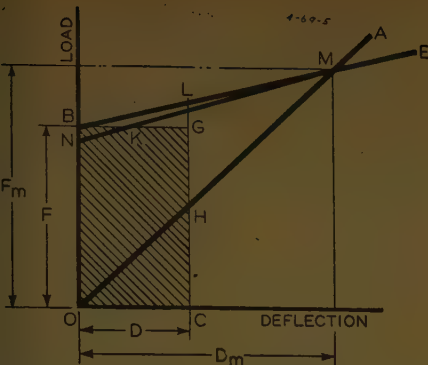


Figure 5. Graphical representation of characteristics of preloaded contact springs

or without making the mechanism undesirably small.

Analysis indicates that there is oblique impact between the blade and the stationary contact which tends to cause a rebound at an angle. It seems quite clear that, without the application of some

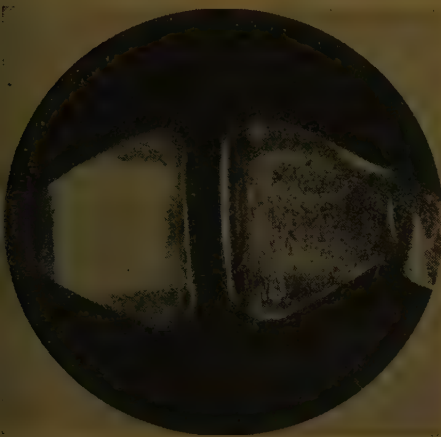


Figure 6. Right switch blade contact after 60,000 closures of circuit containing lamps. Left blade unused

external force, the blade after impact will separate from the contact, if the blade is a free acting spring. Rebound may be prevented by preloading the blade to the extent necessary to reduce to zero the kinetic energy component perpendicular to its travel.

In Figure 5:

D = blade travel after impact within which rebound energy is to be absorbed
 F = average force which, acting through distance D , is equivalent to the kinetic energy component perpendicular to the blade travel
 D_m = maximum blade deflection
 F_m = maximum blade pressure

The work represented by the area $OBGC$ is equal to the kinetic energy of the component of rebound perpendicular

Snap switch with preloaded contacts closing noninductive resistance circuit on 45 volts direct current

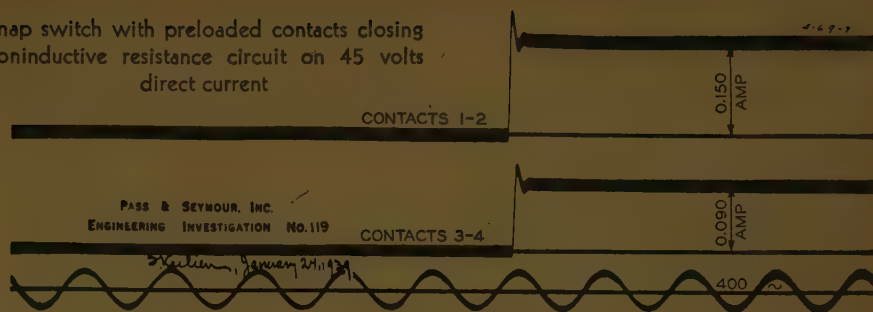


Figure 7. Oscillogram showing vibrationless contact closures of preloaded blade contacts

to the blade travel. This is the amount which must be balanced by the work of deflecting the blade.

The load deflection curve OA represents a spring blade of suitable characteristics to give adequate contact pressure F_m at maximum deflection D_m , but it is seen that the area, OHC , representing the work done in deflecting the spring distance D , is less than $OBGC$ and, therefore, insufficient to prevent rebound.

The spring blade, however, which will just prevent rebound, will have a load deflection curve NM with ON representing the preload. Or a spring having the loading characteristic BE will provide a factor of safety.

To check the results experimentally, a number of switches built with the blades of suitable design were tested under most severe practical load (tungsten filament lamps with a special generator capable of producing the high surges needed.)⁴ The test specimens were arranged so that the contacts were only "making" under load, while the "breaking" of the circuit was accomplished by another device. There was no visible pitting on any specimen, indicating vibrationless "make," even after 60,000 operations. The appearance of a specimen after test is given in Figure 6, in which the right-hand contact discloses slight grooves resulting from mechanical abrasion of parts. The left-hand blade is an unused sample and is shown for comparison.

Oscillograms further substantiated vibrationless contact (see Figure 7), for the circuit controlled by the contact was not broken after the initial "make." The slight saw-tooth shaped lines at the start of "on" period and at the end of "off" period, as shown on this and previously mentioned oscillograms, represent the record of the galvanometer over-travel, and should not be interpreted as circuit interruptions.

In actual practice the contact is called upon not only to "make" but also

to "break" the lamp load circuit. Injuries to contact surfaces resulting from "breaking" contribute to their imperfect "making," ultimately destroying the contacts in spite of the designs, exposing different areas of the contact during "making" and "breaking." The life of switches having preloaded blades has been increased several times as compared with that of a conventional design having no vibration suppression means. This fact has been substantiated by tests of a large number of specimens.

It is quite apparent that designing the contacts so that the energy causing vibration is absorbed at the instant of impact may be readily accomplished by the mutual preloading of the contact blades. Under such conditions the vibration may be eliminated completely, producing a marked increase in the longevity of electric contact.

There is a tendency to increase the load controlled by switch contacts, particularly in the field of lighting. This condition has been created by higher levels of illumination and the impracticability of increasing the number of conductors in existing wiring. Short life may be expected in such cases with switches whose contacts are not suitably designed. Wider application of various contactors, relays, industrial switches, and more stringent requirements in their performance emphasize the necessity of having vibrationless contacts. The described method of vibration suppression, because of its simplicity, could be applied successfully to many switching devices whose vibrationless contact operation is paramount for reliable performance.

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A New Three-Element Current-Limiting Power Fuse

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Synopsis: In order to meet the requirements for the protection of high-voltage motor starters and for protecting small loads and apparatus connected to those parts of electric systems having extremely high short-circuit currents, it has been necessary to increase the current range of the three-element current-limiting fuse. This fuse, which was announced in 1940, has been in commercial use for over two years in the lower ampere ratings.

The development of higher current ratings in a fuse of suitable dimensions produced problems and solutions totally different from those previously encountered. A new type of fusible element has a time-current characteristic particularly suited to current-limiting fuses. Extremely fast melting times on high currents to give correct current-limiting action are combined with a continuous current-carrying capacity and normal melting time of an element having five times the area previously associated with the current-limiting characteristic. The association of this element, with gas-evolving material and quartz sand to give quick and positive current limitation while the metal vapors are absorbed, results in an entirely new fuse construction. The combination of this current-limiting element with a noninductive resistor of special characteristics and a totally enclosed boric-acid "clean-up" fuse has resulted in a current-

limiting fuse of more compact construction than has been available heretofore in the ratings involved. Exhaustive tests have demonstrated the suitability of the new fuse for application on high-capacity systems to interrupt the full range of fault currents with minimum system disturbance.

IN order to meet the requirements for a fuse of small size with current-limiting characteristics for connecting light loads and small apparatus to high power systems, a new form of current-limiting fuse was developed and announced in 1940. Three distinct elements characterized this fuse.

1. A current-limiting fusible element which produced a high arc voltage to limit the current.
2. A resistor in parallel with the fusible element to limit the voltage to a predetermined value.
3. A series fuse to interrupt the power follows current through the resistor.

The fuse proved capable of interrupting the highest currents, up to 130,000 amperes at 13,200 volts, without producing voltages in excess of 150 per cent of the peak circuit voltage.

The excellent service record of fuses built with this principle and the inherently higher interrupting ability of current-limiting fuses, coupled with the necessity for limiting the fault current in

motor starters and similar apparatus, make it desirable to extend the current range of the current-limiting fuse announced in 1940. In considering the desirable limits in current ratings for current-limiting fuses, the following factors must be considered:

1. The effect of current rating on the current-limiting characteristic. As the current rating of a current-limiting fuse increases, the current to which a fault can be limited also increases, thereby nullifying the beneficial effects of a current-limiting fuse. By reference to Figure 1 it can be seen that the current-limiting effect of a fuse rated above 200 amperes would be appreciable only on systems having high values of short-circuit current.
2. Current-limiting fuses for motor starters are required to have high current ratings with moderate interrupting capacity, whereas current-limiting fuses for station auxiliaries and similar services are required to have high interrupting capacity and relatively low current ratings. The heavier current distribution service can be fulfilled more economically by fuses of lower interrupting rating.

From a consideration of these factors it would seem desirable to extend the new current-limiting fuse to cover a continuous current rating of 200 amperes for voltages through five kilovolts for motor-starter applications, and to cover continuous current ratings of 100 amperes for voltages above five kilovolts to permit tapping small loads from high-capacity systems. Edison Electric Institute and National Electrical Manufacturer's Association have adopted recently the "E" rating for power fuses, which specifies that fuses will carry 100 per cent of rating continuously and melt in exactly five minutes at 200 to 240 per cent of the rating for fuses 100 amperes and below and in exactly ten minutes at 220 to 264 per cent of rating for fuses above 100 amperes. It is seen readily that, for "E"-rated fuses, the proposed ratings cover a wide field of application.

Figure 2. Construction of 2.5-kv 200-ampere three-element current-limiting fuse

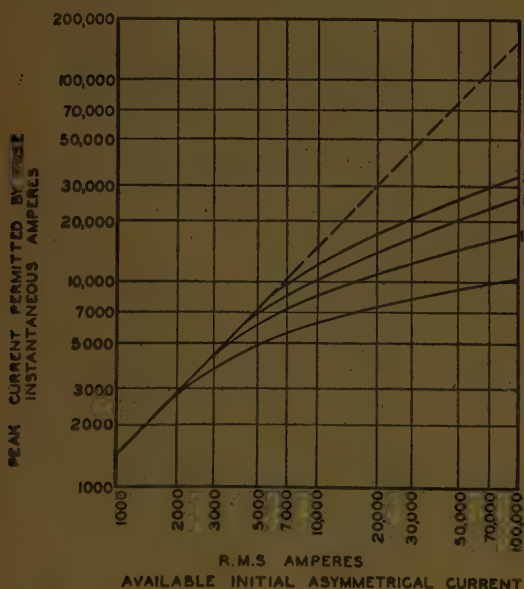


Figure 1 (left). Current-limiting characteristic curves showing maximum peak current permitted by new three-element power fuse for all values of available short-circuit current

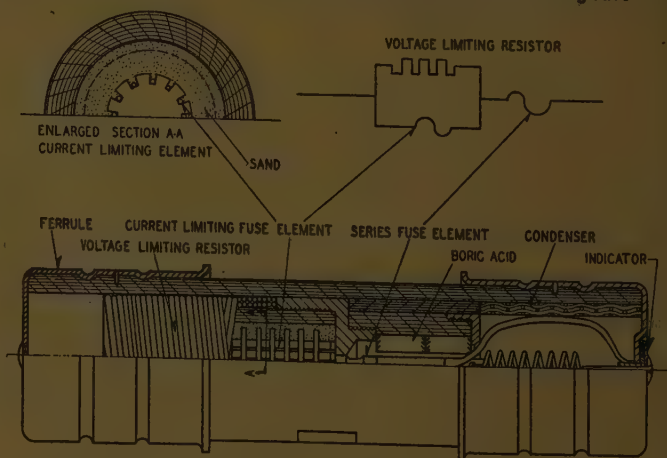




Figure 3. Five-kilovolt 200-ampere fuse unit in disconnecting-type mounting

In extending the current range of the fuse embodying the new current-limiting principles, it was recognized soon that the same materials and construction as used in the lower ampere ratings could not be used without resulting in a fuse of prohibitive size and cost. The 200-ampere rating could not be obtained in a single fuse of reasonable proportions with proper current-limiting characteristics simply by increasing the number of parallel silver wires in the current-limiting element.

The parallel resistor which diverts cur-

rent from the current-limiting element required radically different characteristics in order to handle the higher currents in a device of reasonable dimensions. The absorption of metal vapors from a new type of heavier fuse element required a novel construction.

The development of higher current ratings, therefore, produced problems and solutions completely different from those in the lower current ratings.

Construction of the New Fuse

The electrical and physical relationship of the three basic elements in the new fuse are shown in Figure 2, while the overall appearance of a complete fuse with disconnect mounting is shown in Figure 3. As in the current-limiting fuse for lower current ratings announced in 1940, the new power fuse comprises a current-limiting element shunted by a resistance or voltage-limiting element with a series "clean-up" element. All three of these elements are contained in a simple non-renewable cartridge that is much smaller than existing indoor-type power fuses of lower interrupting capacity and smaller than conventional current-limiting fuses of equal rating. The outer casing of heavy Micarta tube with spun-on ferrules contains in one end the assembly,

consisting of the current-limiting element and shunt resistor; immediately adjacent is the series-calibrated fuse element in its boric-acid-lined chamber, which on interruption exhausts into the condenser in the other end of the casing.

The heart of the new power fuse is the current-limiting element which is contained in a high-strength fibre tube with threaded ferrules. The conducting portion of the current-limiting element consists of a plurality of specially rolled silver wires supported in a slotted fibre bar. As shown in Figure 4, each silver wire has the appearance of a string of sausages. This construction is obtained by rolling a large diameter wire with reduced sections of approximately one sixth the cross section of the main wire. The restrictions are spaced equally at intervals throughout the length of the conductor. The grooves in the fibre support are approximately twice as deep and slightly wider than the diameter of the silver conductor. The conductor wires are placed in the bottom of the grooves in intimate contact with the fibre, except on the open side of the groove. Fibre washers equally spaced on the slotted fibre bar retain the conductors in the grooves. The space between the fibre support and the fibre casing is filled with a coarse quartz sand of uniform size.

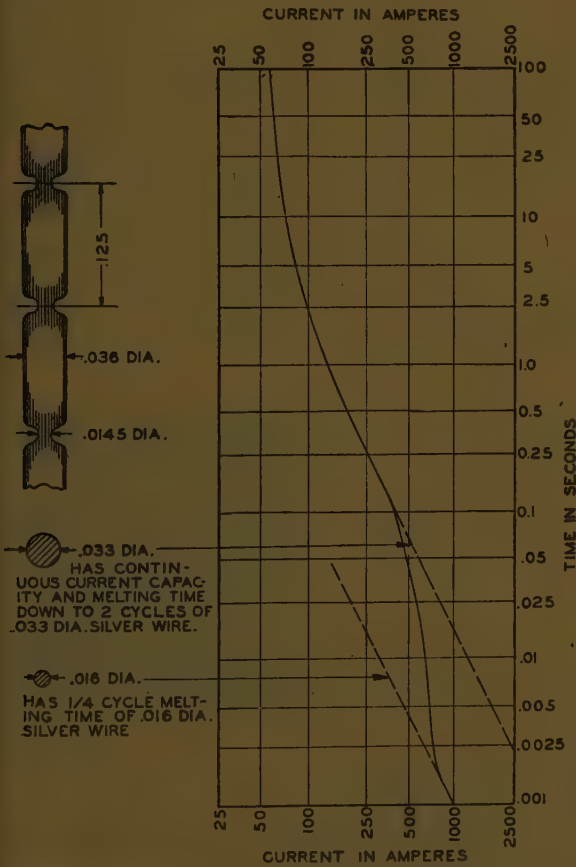
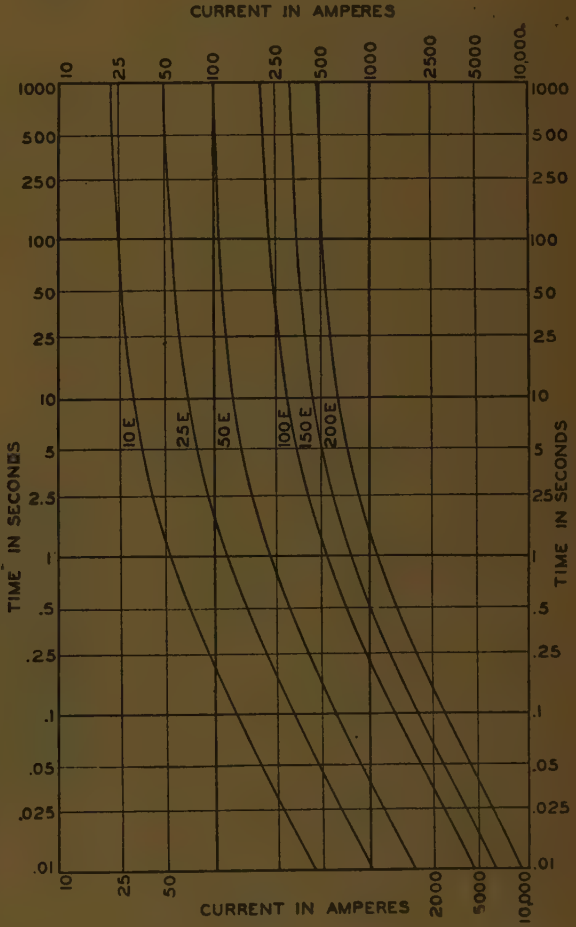


Figure 4 (left). Enlarged view with melting-time-current curve of individual current-limiting fuse element

Figure 5 (right). Minimum-melting-time-current characteristics of representative current ratings of three-element power fuse



The shunt resistor or voltage-limiting element which eliminates high-surge voltages incident to current limitation is connected permanently in parallel with the current-limiting element. The resistor consists of two insulated resistance wires wound directly onto the fibre shell of the limiter element and connected on each end to the limiter ferrules. The two layers of resistance wire are wound in opposite directions to minimize inductance. The special resistance wire is essentially nonmagnetic, possesses the virtue of having a moderate positive temperature coefficient of resistance, and has the proper specific resistance for the resistances and sizes needed.

The melting time-current characteristics of the fuse, as shown in Figure 5, are determined by the calibrated element in the boric-acid series fuse. This element is a low-temperature type which consists of a heater and fusible alloy for long melting time characteristics and a reduced fusible section for short melting time characteristics. The series-fuse member is spring withdrawn through the boric-acid-lined interrupting chamber into the condenser to insure fast clearing of low current faults. The condenser consists of several layers of coarse-mesh copper screen which presents the maximum surface to condense the steam evolved from the boric acid during interruption. The action of the operating spring mechanically releases an indicating target outside the ferrule.

Operation

The magnitude of fault current determines which of two ways the fuse shall operate. On currents of overload magnitude the series fuse operates in the same manner as the totally enclosed boric-acid power fuse. The blast of steam from the boric acid deionizes and extinguishes the arc, while the copper screen condenses the steam to water. During this process the current-limiting elements do not fuse and play no part in the interruption.

On short-circuit currents where the series fuse element melts in a small fraction of a cycle, the current-limiting element melts almost simultaneously. The fusion of the current-limiting element and the action of the resultant arcs in the restricted fibre slots tend to produce an arc voltage sufficient to prevent further increase in the fault current and transfer the current to the shunt resistor. In order to eliminate high pressures within the current-limiting chamber, coarse silica sand is used to condense the metal

vapors from the fusible elements and cool the fibre gases.

The resistor in parallel with the current-limiting element, being noninductively wound, will stabilize the voltage that occurs during interruption. The maximum voltage that can appear is simply the IR (current-resistance) drop through the resistor. When the instantaneous peak current permitted by the current-limiting element, which can be determined from the curve shown in Figure 1, is known, a value of resistance may be chosen to limit the voltage to any desired figure. It has been determined by repeated tests, however, that all of the current does not transfer instantaneously to the resistor. On high current interruptions approximately 25 per cent of the peak current will continue to flow through the current-limiting element for a short time, resulting in a peak voltage 25 per cent less than the calculated value. In addition to controlling the voltage surges during interruption, the resistor very materially reduces the duty on the current-limiting element. The total energy absorbed by the current-limiting element is less than 15 per cent of the energy that it would absorb without the parallel resistor. This makes possible a very compact current-limiting assembly and is a material factor in the small over-all size of the complete fuse.

On the high values of short-circuit currents where the series-fuse element melts almost simultaneously with the current-limiting elements, the series fuse arcs throughout the current-limiting action and interrupts the resistor current at the first current zero. Since this current is resistance limited, it is very easily interrupted.

The New Fusible Element

Of particular interest and importance is the new current-limiting fusible ele-

ment. Although various shapes and sizes of fusible elements have been used to obtain different desired characteristics, there have never been any designs to obtain the peculiar characteristics desired in a current-limiting fuse. The element shown in Figure 4 has all the normal characteristics desired in a fuse for time values in excess of approximately two cycles, and yet for short times of less than one-quarter cycle, it has a very fast melting time. This shift in characteristics results in a fuse that limits the current to 38 per cent of the value that would be obtained if simple straight wires were used. The use of these fusible elements makes possible the cool operation of the high current ratings when carrying full-rated current.

Summary of Tests

The thorough testing of current-limiting fuses involves testing under all degrees of asymmetry as well as on high and low fault currents with various circuit constants, since the severity of duty on the various components of the new current-limiting fuse varies with the point on the generated voltage wave that the current-limiting fuse element melts. A synchronous short-circuiting switch may be used conveniently to obtain these various degrees of asymmetry. The maximum duty on the current-limiting element and the maximum voltage surge due to current limitation occur when fusion of the current-limiting element occurs at normal voltage peak, since at this point the induced voltage due to the stored magnetic energy of the system is at peak value and adds directly to the generator voltage, thereby giving maximum voltage across the limiting element, tending to force current through it. The maximum duty is imposed on the parallel resistor and boric-acid series fuse when current limitation occurs just after

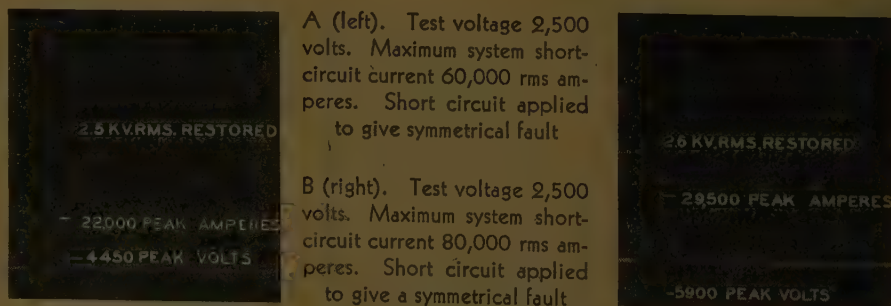


Figure 6. Magnetic oscillograms of interrupting tests on 2.5-kv 200-ampere three-element current-limiting fuse

Note higher peak voltage and longer duration of current resulting in more severe duty on the asymmetrical test

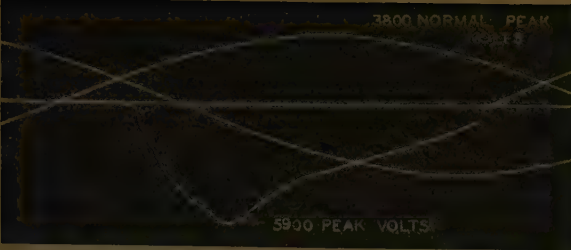


Figure 7. Cathode-ray oscillogram of voltage during interruption by 2.5-kv 200-ampere fuse shown on magnetic oscillogram, Figure 6B

elements combined with the low-temperature-type series fuse makes possible the highest desirable current rating in a single fuse unit. On temperature rise tests the 200-ampere fuse carries full rated current without exceeding 30 degrees centigrade rise on the ferrules above a 40-degree-centigrade ambient temperature.

In addition to interrupting tests on the fuse units alone, numerous combination tests have been made with new motor starters throughout the entire current range from overload currents, which the starter interrupts without melting the fuse, to the highest values of short-circuit current, for which the fuse is designed, in which case the fuse interrupts the fault with no damage to the starter. A starter for such combination service must be designed for the particular duties involved.

Conclusions

The current ratings of the three-element current-limiting fuse have been extended by the adoption of new features. Of particular importance is the current-limiting fusible element that gives a time-current characteristic particularly suited for current-limiting fuses. The new features combined in a compact structure permit current ratings ample to protect high-voltage motor starters, other types of apparatus, and small loads connected to high power systems. The new power fuse has the desirable qualities of the lower-current three-element current-limiting fuses in that the voltages during interruption are controlled definitely to eliminate harmful overvoltages.

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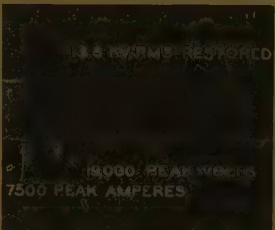
voltage zero, and these two elements carry current until the next voltage zero.

Consider the case of a high-ampere-capacity fuse where an appreciable time is required for melting the current-limiting element. If the fault is initiated at zero voltage, the system voltage will be approaching normal peak value when fusion occurs. Since this condition imposes the most severe duty on the limiter, it follows that an asymmetrical fault represents the most difficult problem of inter-

the fuse. Representative magnetic and cathode-ray oscillograms are shown in Figures 6 to 8. The magnetic oscillograms clearly show when current ceases to flow in the current-limiting element, as indicated by the voltage trace changing from a high arc voltage to the smooth sinusoidal form of the generator voltage, and the current trace simultaneously changing from a rapid decline to a sinusoidal form modified by the increasing resistance of the shunt-voltage-limiting



A. Five-kilovolt 200-ampere fuse. Test voltage 5,000 volts, available short-circuit current 60,000 rms amperes



B. 15-kilovolt 25-ampere fuse. Test voltage 13,800 volts, available short-circuit current 90,000 rms amperes

Figure 8. Magnetic oscillograms of interruptions

Short circuit applied to give asymmetrical fault

ruption for high-ampere-capacity fuses. On low-current fuses, where fusion of the current-limiting element occurs in a very short time interval, a fault initiated just prior to normal voltage peak or a symmetrical short circuit represents the most severe duty. Therefore, the degree of asymmetry required for the most difficult operation is a variable depending on the current rating of the fuse and the magnitude of the available short-circuit current.

Consequently, all ratings of fuses have been tested at rated voltage with all conditions of asymmetry on currents of varying magnitudes from minimum melting current up to the interrupting rating of

element. The cathode-ray oscillograms show that the surge voltage accompanying current limitation does not exceed 160 per cent of normal system voltage on the highest asymmetrical fault currents with high-current fuses. This combination represents the condition under which maximum voltage will be obtained. With any other degree of asymmetry or lower fault current the voltage surge will be less.

A comparison of the magnetic and cathode-ray oscillograms shows that a quick response magnetic oscillograph is entirely adequate for measuring the voltage phenomena of this fuse.

The design of current-limiting fusible

Thermal Protection of Transformers Under Overload Conditions

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Synopsis: The overloads recommended in the AIEE transformer subcommittee's report,¹ "Emergency Operation of Transformers," are based on considerably higher transformer hot-spot temperatures for short-time operation than those given in and used to derive the emergency overloads recommended in the American Standard Guides for Operation of Transformers and Regulators C-57.3.

Overloads may be obtained in close agreement with the recommended emergency overload curves by the use of a relay which is controlled by a specially designed heating coil or by a specially designed relay with a conventional heating coil. Since a relay operates at about the same temperature irrespective of time to avoid too high hot-spot temperature for ultimate conditions, the relay and heating coil must have such characteristics as to permit the transformer hot-spot temperature to reach considerably higher values for short times than for ultimate steady-state conditions. A detailed study of this problem has shown that this may be accomplished satisfactorily by the use of a lagged heating coil which has a relatively large time constant in comparison with that of the transformer winding or by the use of a heating coil, the time constant of which is about the same as that of the winding for operating a relay that is compensated for the changes in ambient temperature.

This relay which has been developed can be set to perform three separate functions: control fans, give a warning signal, and sound an alarm or, if desired, trip the transformer off the circuit. A diagrammatic sketch and photographic prints show the various combinations of bulbs and relays available. It is believed that the relay allows the transformer to be loaded more nearly in agreement with the recommended industry loadings than any previous available device.

THE AIEE transformer subcommittee¹ has recommended higher overloads than those given in the ASA Guides for operation of transformers.

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These overloads are set up on the assumption that, under rare emergency conditions, it is better to use up a small amount of the expected life of the transformer than to have an interruption of service. Therefore, as a result of the work of the AIEE and the ASA, a demand is developing for a relay that will close its contacts when the limiting load condition is reached.

Since these emergency overloads are based on hot-spot temperatures, the most direct way of safely utilizing the extra capacity would be to furnish a relay with the proper time-temperature characteristics and to operate it from a standard artificial hot-spot heater element. While it may be possible to design such a relay, it does not appear practical, because a relay is normally sensitive to temperature but not to time when it is longer than several minutes; consequently, other means are suggested as follows:

1. To operate a fixed temperature relay from a lagged heating coil (immersed in the cooling fluid),* the time constant of which is many times that of the transformer winding, so that the relay does not reach its operating temperature until the winding temperature and load have risen to the desired value.
2. To operate a relay having an ambient-temperature correction from a heating coil, the time constant of which is the same as that of the transformer winding.

An extensive investigation has shown that, in order to obtain satisfactory results under all conditions, a part or all of the following factors should be taken into consideration:

1. Transformer characteristics—hot-spot rise, top oil rise, oil time constant, and ratio of losses.
2. Time constant of the heating coil immersed in the oil.
3. Temperature rise of heating coil over oil at rated load.
4. Relay operating temperature.
5. Effect of ambient temperature on relay operating temperature.

The purpose of this paper is to show what has been done in meeting the recommended emergency overload curves by taking into account the previously

* The cooling fluid may be mineral oil or any of the noninflammable synthetic liquids (Askarels) developed for transformer use.

mentioned factors. Finally, calculated overloads obtained with thermal protection on transformers with average characteristics are compared with the rare emergency overloads recommended in the AIEE interim report¹ and the usual emergency overloads recommended in the ASA Guides for operation of transformers, C-57.3.

Design of Heating Coil to Meet the Overload Requirements

The use of an ordinary hot-spot indicator and a standard thermostat for overload protection is impractical, because the thermostat, operating relatively quickly at a fixed temperature, could not distinguish between long and short-time intervals and, hence, would operate too quickly in the short-time range, or vice versa.

It is well known that the oil of a transformer has a time lag of several hours due to the total heat-storage capacity of the transformer, whereas, the time lag of winding rise over oil is in the order of 15 to 20 minutes. This means that a relay operated by oil temperature alone would permit excessive winding temperatures under short-time heavy overload conditions, particularly in low ambient temperatures. The scheme of using a thermal relay (immersed in the transformer oil), the temperature rise of which is responsive to load current, has been described² and has been in use for several years for thermal protection of transformers.

To obtain satisfactory results with a scheme employing a relay responsive to load current, the temperature rise of the relay (or of a heating coil controlling the relay) must be less than the hot-spot rise over top oil at rated load. Furthermore, the relay must be set to close its contacts at some temperature above that resulting from 100 per cent ultimate conditions in a 30-degree-centigrade ambient temperature. Then on overloads, by the time the temperature of the relay has reached its tripping point, the hot-spot rise will have attained higher values for the higher overloads. It is this difference in the rate of temperature rise that allows the higher hot-spot temperatures for the short-time overloads.

However, if the ambient temperature changes, this scheme does not give correct results in that, if set to allow correct short-time loading at the higher ambient temperatures, it allows too high loadings at the lower ambient temperatures. This deficiency can be corrected by introducing an ambient-temperature

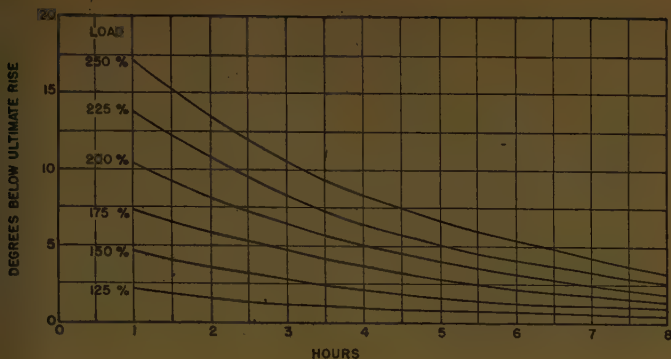


Figure 1. Depression (degrees below ultimate rise) curves for lagged heating coil immersed in oil of transformer under overload conditions following full load

Transformer-oil time constant = 4.0 hours

correction in the mechanism of a relay (mounted on the outside of the transformer), the contacts of which are operated by a bulb enclosed in a heating coil immersed in the top oil and responsive to the load current. On the other hand, if the heating coil is suitably designed and lagged, the ambient-temperature correction can be omitted. By choosing the proper temperature rise of the heating coil (either the lagged or unlagged) and by selecting the right tripping temperature of the relay, a wide flexibility is secured, thereby enabling one to design a protective system to function correctly for almost any condition of loading.

In connection with the use of a lagged heating coil, as long as it was only necessary to meet the ASA emergency overloads, a small amount of lagging was sufficient. However, when the AIEE transformer subcommittee set up the rare emergency overloads based on considerably higher short-time hot-spot temperatures than used in setting up the ASA emergency overloads, it became necessary to modify the design and characteristics of the thermal relay and increase the lagging effect to meet the new conditions. The time constant of the lagged heating coil is now much more than that of the transformer winding.

Table I. Comparison of AIEE and ASA Recommended Overloads With Overloads Permitted by the Protective System

	AIEE Emergency (Times Rated Load)			ASA Emergency (Times Rated Load)	
	Hours	By Relay	Recommended by AIEE*	By Relay	Recommended by ASA
Self-Cooled					
Following full-load 30-degree ambient temperature.....	24.....	1.37.....	1.25.....	1.15.....	1.1.....
	8.....	1.41.....	1.35.....	1.17.....	1.15.....
	4.....	1.52.....	1.5.....	1.22.....	1.2.....
	2.....	1.7.....	1.7.....	1.30.....	1.3.....
	1.....	1.9.....	1.9.....	1.4.....	1.4.....
Following full-load zero-degree ambient temperature.....	24.....	1.62.....	1.55.....	1.42.....	1.4.....
	8.....	1.69.....	1.65.....	1.47.....	1.45.....
	4.....	1.84.....	1.8.....	1.57.....	1.5.....
	2.....	2.1.....	2.0.....	1.75.....	1.6.....
	1.....		2.0.....	2.0.....	1.7.....
Following no-load 30-degree ambient temperature.....	24.....	1.37.....	1.25.....	1.15.....	1.10.....
	8.....	1.47.....	1.45.....	1.3.....	1.25.....
	4.....	1.71.....	1.7.....	1.42.....	1.35.....
	2.....	2.05.....	2.0.....	1.7.....	1.50.....
	1.....		2.0.....	2.1.....	1.60.....
Following no-load zero-degree ambient temperature.....	24.....	1.62.....	1.55.....	1.42.....	1.4.....
	8.....	1.75.....	1.75.....	1.55.....	1.55.....
	4.....	2.0.....	2.0.....	1.75.....	1.65.....
	2.....		2.0.....	2.15.....	1.8.....
	1.....		2.0.....	2.6.....	1.9.....
Forced-Air-Cooled					
Following full-load 30-degree ambient temperature.....	24.....	1.7.....	1.53.....	1.52.....	1.46.....
	8.....	1.72.....	1.66.....	1.55.....	1.53.....
	4.....	1.8.....	1.8.....	1.6.....	1.6.....
	2.....	1.94.....	1.93.....	1.73.....	1.73.....
	1.....	2.13.....	2.13.....	1.88.....	1.86.....
Following full-load zero-degree ambient temperature.....	24.....	1.94.....	1.755.....	1.8.....	1.685.....
	8.....	1.97.....	1.855.....	1.82.....	1.755.....
	4.....	2.07.....	2.025.....	1.9.....	1.825.....
	2.....	2.27.....	2.155.....	2.1.....	1.95.....
	1.....	2.50.....	2.355.....	2.3.....	2.085.....

* The maximum load recommended is two times rated load. For forced-air-cooled rating the maximum load recommended is 2.66 times the self-cooled rating.

The problem of calculating the temperature rise of the heating coil (over top oil) to obtain the right time constant under the new condition was found to be very complicated. Tests have shown that, for a transformer winding or a heating coil with no special lagging, the ultimate rise is reached in approximately the same time (15 to 20 minutes), whether the oil temperature is constant or is increasing. However, when a heating coil is lagged, so that it reaches ultimate rise in a given time in oil at a constant temperature, it requires a much longer time to reach its ultimate rise when immersed in oil, the temperature of which is increasing. Theoretically, its rise does not become constant so long as the temperature of the oil is increasing, but it becomes practically constant in eight to ten hours, as illustrated by the "depression curves" (degrees centigrade below ultimate rise), calculated by equation 2 and shown in Figure 1.

The transient temperature rise of this lagged heating coil can not be calculated by an equation of the form usually used² for determining the hot-spot rise of a transformer over the oil, that is

$$\theta = \theta_u (1 - e^{-\frac{T}{B}}) \quad (1)$$

but an entirely different formula* must be used, namely

$$\theta = \theta_u - \left(\frac{FB_e}{B_0 - FB_e} \right) \left(\phi_u e^{-\frac{T}{B}} \right) \quad (2)$$

where

θ = temperature rise of heating coil over oil, degrees centigrade

θ_u = ultimate temperature rise of heating coil over oil, degrees centigrade

F = factor allowing for the effect of distributed thermal capacitance of the lagged heating coil

B_e = time constant of heating coil

B_0 = time constant of transformer oil

ϕ_u = ultimate temperature of transformer oil above the starting temperature, degrees centigrade

$e = 2.718$

T = time

Many heat runs ranging in time from one to eight hours' duration were made on a 2,500-kva transformer with heating coils having different lagging, to check equation 2 and to obtain sufficient empirical data on factor F for design purposes.

The fortunate phenomenon, whereby a rising oil temperature gave the heating coil an unexpected long time lag, helped to make it possible to design a thermal protective scheme to meet the wide variety of requirements. In order to take

* See appendix for derivation.

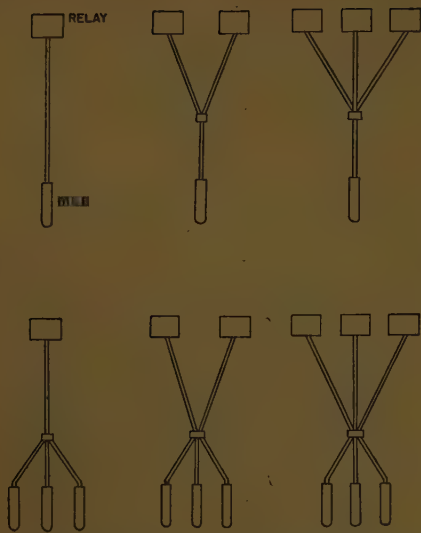


Figure 2. Six combinations of bulbs and relays available for thermal protection of transformers

full advantage of this time lag, however, the temperature rise of the heating coil over oil at rated load (since its time constant is affected by the time constant of the transformer under overload conditions) and the temperature at which it operates the relay must be selected on the basis of the individual transformer characteristics and the kinds of overloads required. Its flexibility enables one to meet almost any requirement.

Factors Affecting and Calculation of Transformer Temperature Rises

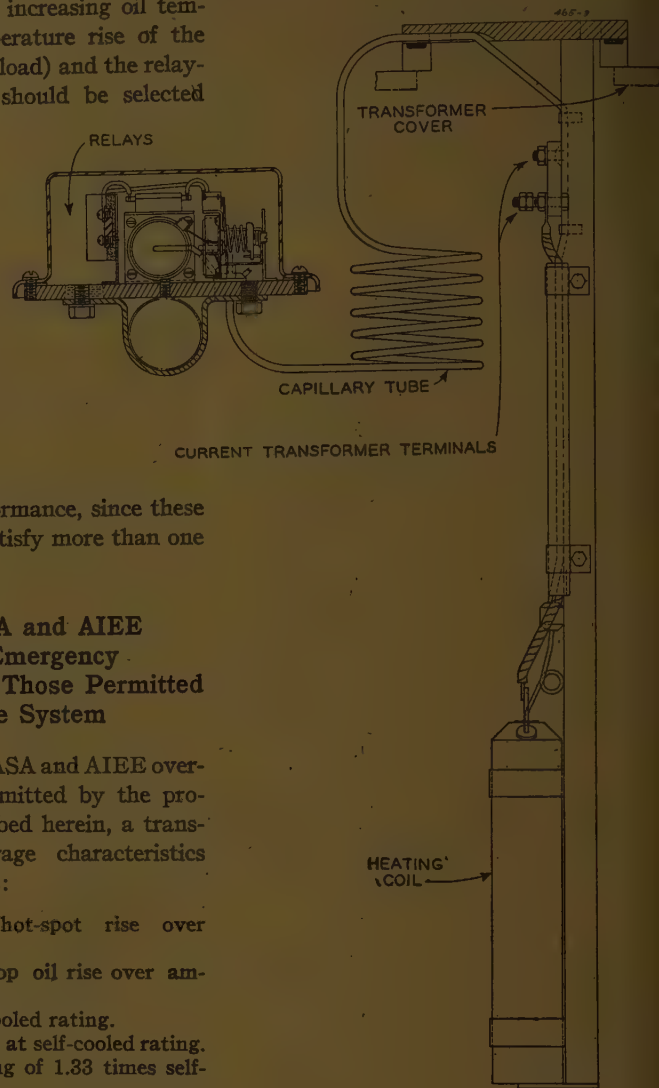
Some of the more important factors that determine short-time overloads are the oil time constant and hot-spot rise over top oil. Self-cooled oil time constants ranging from three to five hours were chosen as representative for most transformers. A survey of many recent designs for medium-size power transformers shows that the average time constant is approximately four, extreme limits being as low as three and as high as seven. For the forced-air-cooled oil-immersed ratings (1.33 times the self-cooled rating) the time constant is, of course, less, since the oil rise is much less for a given loss. Two thirds of the self-cooled oil time constant was used in calculating the forced-air-cooled loadings.

As pointed out in the paper by Montsinger and Ketchum,³ the hot-spot rise over average winding rise in most modern transformers ranges from five to ten degrees centigrade, and for this reason it is believed that a hot-spot rise of 62 degrees centigrade (55+7) represents the average condition. This value is used later.

A formula of the general form of

equation 1 should be used to calculate the oil rise before conditions become constant. Equation 2 should be used to calculate the temperature rise of a lagged heating coil over the increasing oil temperature. The temperature rise of the heating coil (at rated load) and the relay-closing temperature should be selected

Figure 3. Heating coil and relays



to give the best performance, since these must apply to and satisfy more than one operating condition.

Comparison of ASA and AIEE Recommended Emergency Overloads With Those Permitted by the Protective System

For comparison of ASA and AIEE overloads with those permitted by the protective system described herein, a transformer having average characteristics was chosen, as follows:

- 62-degree-centigrade hot-spot rise over ambient temperature.
- 48-degree-centigrade top oil rise over ambient temperature.
- 3:1 loss ratio at self-cooled rating.
- 4.0-hour time constant at self-cooled rating.
- Forced-air-cooled rating of 1.33 times self-cooled rating.

Table I shows how well the recommended overloads can be followed with the new protective system. For the ASA emergency loads the hot-spot temperatures are below 105,* 110,* 113, 115,* and 120 degrees centigrade for 24, 8, 4, 2, and 1 hours, respectively, in 28 out of 30 conditions shown in Table I. The two cases are: 4 degrees high for 8 hours and 8 degrees high for 24 hours. Both cases follow full load in 30 degrees ambient temperature for forced-air-cooled conditions. No comparison of loads is shown for forced-air-cooled rating following no load, because this is a condition that is not very likely to occur.

For the AIEE emergency loads the hot-spot temperatures are below the recommended values for the short times but above the recommended values in all cases for 24 hours, and in some cases for

* Recommended by American Standard C-57.3 section 11.002 (C).

8 hours. The principal reason for this is that the temperatures are nearly enough constant in 8 hours' time to produce (with the small difference in loads permitted by

the relay for 8 and 24 hours) approximately the same hot-spot temperatures as against a difference of 10 degrees centigrade in the recommended values of 120 degrees centigrade for 8 hours, 110 degrees centigrade for 24 hours. Both the 24-hour loads and hot-spot values may be reduced by insulating a heating coil sufficiently to produce a 24-hour temperature lag, but this is not ordinarily practical.

It seems reasonable to assume that, in most emergencies, lasting 24 hours or more, the daily peak load would not be on more than eight hours. Furthermore, as these overloads are intended for rare emergency conditions, once a year or less often (once in 16 years, as estimated in L. W. Clark's paper),⁴ the amount of aging at somewhat higher than recommended values for the full 24 hours should be acceptable.

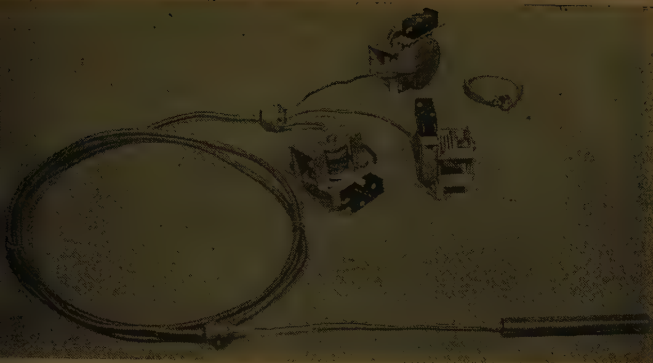


Figure 4. View of bulb, capillary tube, and relays

For transformers having characteristics quite different from the aforementioned, it will be necessary, of course, to use a different tripping temperature for the relay and perhaps a different heating-coil rise at rated load.

Where the load permitted for one or two hours is above the maximum load recommended by AIEE (two times rated load), and it is desirable to limit the maximum load to this value, other means, such as overload current relays, must be arranged to come into action when the maximum desirable load is exceeded. For forced-air cooling two times rated load corresponds to 2.66 times the self-cooled rating.

In general, when the wide range of operating conditions covered is considered, the overloads line up remarkably well with the recommended values, in fact, far better than appeared possible when the problem was attacked first. If the planned conservatism of the ASA and AIEE recommendations is considered, the values given seem to be suitable for operation, but it is a simple matter to design for slightly lower loads throughout if desired.

Good results can be obtained also by using a conventional heating coil with a relay designed to close its contacts at lower temperatures in lower ambients.

Relay

In its simplest form the relay includes a bulb heated by a coil and a metallic bellows which operates a switch. The bulb and the bellows are connected through a capillary tube, and the assembly constitutes a closed system which is filled with a volatile liquid. The pressure of vaporization of the fluid is communicated to the bellows and thence to the switch.

Relay Requirements and Functions

The practical application of a relay and its heating coil to transformers having a wide variety of thermal characteristics and load cycle requirements requires certain variable features:

1. The relay contacts must be capable of being set to close over a temperature range of 90 to 130 degrees centigrade.
2. Means must be provided for selecting different temperature rises of the heating coil at rated load.

If a compromise relay setting and temperature rise of heating coil were used, some transformers would be overloaded excessively before the relay came into action, whereas, others would be loaded far below permissible values.

The new relay combination will perform three separate functions:

1. Control the fans used for supplementary cooling.
2. Give a warning signal when an overload has been on the permissible length of time.
3. Give an alarm or, if preferred, trip the transformer off the circuit when the loads exceed specified limits.

The relay can be supplied for all three of the previously mentioned functions or, if fans are not used, with only the signal and alarm circuits. The contacts are standard switches operated by vapor-tension-type bulb and bellows. The bulbs are located in the heating coil and the bellows and switches conveniently located external to the transformer.

Relay and Bulb Combinations

Six combinations of bulbs and bellows, Figure 2, are available. Figure 3 shows a sketch of the heating coil and connections to relays. Figure 4 shows bulb, capillary tube, and three relays. Figure 5 shows three relays assembled on plate of container.

The combinations shown in Figure 2 will take care of all requirements for either single-phase (with two or three windings) or three-phase transformers, that is, one bulb with one bellows will perform one function (turn on fans) on either a single-phase or three-phase unit. One bulb with three bellows will perform all three functions on a single-phase unit, or if desired it will perform the three functions on a three-phase unit satisfactorily if the load is balanced.

Three bulbs with one bellows will perform either one of the three functions on each phase of a three-phase unit or on each of three windings of a single-phase unit. Three bulbs with three bellows will perform the three functions on a three-phase unit with unbalanced loads or on a single-phase unit with three windings.

When three bulbs are used (with either one or three bellows), one in each phase of a three-phase unit or one in each of three windings of a single-phase unit, if the load is unbalanced the bellows are controlled by the temperature in the phase or winding having the greatest load. This is a new feature used for the first time with bellows, although it has been used successfully for several years in controlling three-element hot-spot temperature indicators for three-phase transformers.

These six combinations, therefore, make it possible to obtain practically ideal protection under expected load conditions.



Figure 5. View of three relays assembled on plate of container

Life Test for Accuracy and Reliability

To determine its accuracy in repeated operations one of the relays was given a life test in which approximately 6,000 operations were performed. The maximum variation was in the order of 0.5 degrees centigrade. These tests indicate that the relay has unquestionable reliability.

Means for Checking the Performance of the Relays in the Field

No matter how reliable a device is, it is sometimes desirable to make calibration tests in the field to be absolutely sure that it is in working order, and to accomplish this the relay is provided with auxiliary means to heat the relay under conditions simulating actual operative temperatures.

Application of Relay to Transformers

Several transformers have been and are now being equipped with these new heating coils and relays. The data obtained on the short-time overloads, made on a self-cooled single-phase transformer (rated $H-60$ cycles, 1,250 kva, 69,000 to 7,500/12,975 V volts) equipped with the new protective system, checked the previous tests made to determine the characteristics of the heating coil.

Appendix

Transient Thermal Performance of Transformer-Overload Heating Coil

The transient thermal performance of the heating coil for the transformer overload relay is quite similar to that of a transformer winding, since it is immersed in heated oil and develops an internal temperature rise over oil which must be added to the oil temperature to obtain the temperature of the heating coil. In calculating the transient thermal performance of a transformer winding, it is usually possible to neglect the effect of the rate of change of oil temperature on the temperature rise of the winding above the oil because of the relatively low thermal time constant involved in the transfer of heat from a transformer winding to the oil. For a heating coil having a considerably greater thermal time constant than a normal transformer winding, in calculating the transient thermal performance of the overload relay it is necessary to consider the influence of the rate of change of oil temperature upon the temperature rise of the heating coil over oil. This factor causes the temperature of the heating coil to be somewhat lower during short-time overloads than it would be otherwise and is the primary reason why a heating coil of this nature is so well suited to the control of short-time overloads.

The heating coil includes an assembly containing a loss-producing element and a temperature-sensitive element and having thermal capacitance. This assembly is surrounded by thermal insulation which also has distributed thermal capacitance. It will be assumed that the heating coil can be represented thermally by a suitable value of thermal capacitance and a suitable value of thermal resistance without distributed capacitance. From this assumption it follows that the heating coil will have a thermal time constant which can be determined readily as the product of the thermal capacitance and the thermal resistance. The thermal time constant also can be determined by making a heat run on the heating coil immersed in oil of constant temperature, with constant loss generated in the heating coil, and with the heating coil starting at the temperature of the oil. Under these circumstances the time constant can be determined as the length of time required to reach ultimate heating-coil rise over oil if the initial rate of rise were maintained or as the length of time required to reach 63.0 per cent of ultimate heating-coil rise over oil.

Development of Formula for Calculating the Transient Temperature Rise of a Heating Coil Over Top Oil When the Oil Temperature Is Increasing

KEY TO SYMBOLS

- θ = temperature rise in degrees centigrade of heating coil over oil at any time, T
- θ_u = ultimate temperature rise in degrees centigrade of heating coil over oil for the overload under consideration = $R \times P$
- θ_0 = temperature rise in degrees centigrade of heating coil over oil at start of overload
- B_c = time constant of heating coil in minutes = $R \times C$
- C = thermal capacity of heating coil in watts-minutes per degree centigrade
- R = thermal resistivity of heating coil in degrees centigrade per watt
- ϕ_u = ultimate temperature rise in degrees centigrade of transformer oil for the overload under consideration over the temperature at start of overload
- B_o = time constant of transformer oil in minutes
- P = watts generated in relay during overload
- T = time in minutes
- $e = 2.718$
- F = factor allowing for effect of distributed thermal capacity of the heating coil
- K = constant of integration

The watts loss generated in the heating coil must equal the sum of the watts absorbed and the watts transferred to the oil. When the oil temperature is rising the watts absorbed by the heating coil consist of two components:

1. Watts required to raise the temperature at the same rate as the oil temperature.

2. Watts absorbed because of its rate of rise over the oil temperature.

These relations can be expressed as follows:

$$P = C \frac{d\theta}{dt} + \frac{C\phi_u}{B_o} \left(e^{-\frac{T}{B_o}} \right) + \frac{\theta}{R} \quad (3)$$

If both sides are multiplied by R and θ_u is substituted for RP and B_c for RC

$$B_c \frac{d\theta}{dt} + \theta = \theta_u - \left(\frac{B_c \phi_u}{B_o} \right) \left(e^{-\frac{T}{B_o}} \right) \quad (4)$$

Solving for θ

$$\theta = \theta_u + K \left(e^{-\frac{T}{B_c}} \right) - \left(\frac{B_c}{B_o - B_c} \right) \phi_u \left(e^{-\frac{T}{B_o}} \right) \quad (5)$$

The first term on the right-hand side of equation 5 is the ultimate heating-coil temperature rise over oil which will be realized if the overload is maintained until conditions are constant. The second term is an exponential transient of relatively high decrement. K can be determined by considering conditions at $T=0$. The third term is a long time transient which represents an amount by which the temperature rise of the heating coil is depressed in rising oil on account of the thermal time constant of the heating coil.

In order to apply equation 5 to a heating coil with distributed thermal capacity, it is necessary to determine a thermal time constant which can be used to represent the performance of the relay. Such a time constant can be approximated closely by measuring the time constant by one of the usual methods previously outlined, and by inserting a correction factor F in equation 5 we obtain

$$\theta = \theta_u + K \left(e^{-\frac{T}{B_c}} \right) - \left(\frac{FB_c}{B_o - FB_c} \right) \phi_u \left(e^{-\frac{T}{B_o}} \right) \quad (6)$$

Correction factor F can best be determined by comparing test measurements with equation 6.

When $T=60$ or greater, the term $K \left(e^{-\frac{T}{B_c}} \right)$ can be neglected.

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The Accuracy of Measurements in Lumped R-C Cable Circuits as Used in the Study of Transient Heat Flow

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Synopsis: This paper deals with certain aspects of the accuracy of measurements on lumped R-C cable, and contains definite suggestions as to the desirable number of lumps to be used in such measurements. The effect of capacitive leakage and the influence of sectioning (that is, the influence of the number of lumps) are considered in their relation to the accuracy of measurements of potential and current.

The increasing importance of lumped R-C circuits in heat-transfer research is pointed out, and the analogy between the flow of electricity in such circuits and the flow of heat, particularly unsteady-state or transient heat flow, is treated.

The investigations described in this report were carried out at Columbia University on the heat and mass flow analyzer, which is essentially an R-C circuit. The results can be used in the appraisal of errors encountered in heat flow and similar problems solved by the analogy method, that is, by lumped R-C circuits.

I. Introduction

THE conditions in lumped circuits of this type have been investigated previously.¹ However, these earlier investigations were based mainly on the assumption of ideal capacitors, that is, capacitors which do not leak. Such capacitors are not available. Actual experiments must always be carried out with capacitors which do leak; therefore an investigation of the errors caused by leaking capacitors is appropriate and should prove useful to the electrical engineer, because of the importance of network problems in general.

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Lumped R-C circuits have gained considerable importance in connection with the study of transient-heat-flow problems. The equations for potential and current distribution in a lumped R-C circuit on the terminals of which a voltage is suddenly impressed are identical with those for temperature rise and heat flow in a rod with insulated sides, the ends of which are suddenly exposed to a temperature difference. This analogy is the basis for a method of investigating transient-heat-flow problems, a method which has in recent years found increasing application. In fact, the investigations presented in this paper were prompted by the desire to know more about the accuracy of such a circuit in connection with the application to heat-transfer problems. Although in a number of instances it is possible to compare the results thus obtained with direct thermal measurements or mathematical analysis (see Figure 5 in reference 2, Figures 2 and 4 in reference 6, and Figure 6 in reference 5), in the majority of cases no direct comparison is possible. So far no systematical analysis of the sources of error in this method has been undertaken. This paper presents a first step toward such an analysis.

The application of R-C circuits to analyzing unsteady-state or transient-heat-flow problems has been discussed in a previous paper² by one of the authors. For the use of such circuits, which are the basis of the analogy method—devised first in Europe by C. L. Beuken³—he has developed a tool known as the “heat and mass flow analyzer.” The analyzer, made possible largely through grants from the Research Corporation, has been set up at Columbia University, department of mechanical engineering.

Table I

Thermal Unit	Equivalent Electrical Unit
Temperature difference	Voltage
Heat flow	Electric current
Thermal resistivity	Electric resistivity
Thermal capacity	Electric capacitance

Since the laboratory was first opened in 1940, it has been used extensively for the investigation of heat-transfer problems too difficult to be solved mathematically. A number of these investigations have been published.⁴⁻⁹

The analogy method is based on two principles, namely:

1. The mathematical identity of equations for heat flow and certain electric circuits.

2. The replacing of a circuit with evenly distributed properties by one with lumped properties.

1. The first principle, which is exact, states that the mathematical equations for transient heat flow and for electric resistance-capacitance circuits are identical; hence, by solving an equivalent electrical problem the answer to the thermal problem may be obtained. The solution of the electrical differential equation can be made identical to that of the heat equation by making the proper insertion of equivalent electrical units as in Table I.

2. The second principle, which is an approximation, is that of replacing a differential equation by an equation of finite differences. In the analogy, this means that a body with evenly distributed resistance and capacitance is replaced by a body with “lumped” resistance and “lumped” capacitance. This procedure is common practice in certain fields of electrical engineering.

The study of any thermal problem by means of the analogy method consists of the following steps:

1. Setting up the analogous condition (calculation).

2. Building a resistance-capacitance circuit to represent the heat problem.

3. Subjecting this circuit to the appropriate analogous initial conditions (applying a given voltage at one end of the circuit, which is equivalent to exposure to a given temperature; or applying a current corresponding to a certain heat flow into a body, and so forth).

4. Measuring electrical units—voltage and currents—at points in the circuit analogous to those points at which temperatures and heat flow are to be measured in the body being subjected to heat flow.

5. Converting the results of the electric investigation into heat units (calculation).

A large variety of problems may be solved by the analogy method. The conditions for accuracy are different in each case. The voltage applied, the currents flowing, the duration of the experiment, the length of exposure of various parts of the circuit to higher voltages, even the atmospheric conditions in the laboratory—all influence the results.

For the investigation a particular type of problem was chosen, a type which may be considered as basic to the method in

general. This problem can be stated as follows: "An R - C circuit, initially at zero potential, is suddenly exposed to a potential difference, both ends of the circuit being connected to the supply system by noncapacitive resistances." In thermal terms this problem may be expressed as follows: "A wall, initially at zero temperature, is suddenly exposed on one surface to a finite higher value of temperature, while the ambient facing the other surface is held at the initial temperature. What is the temperature-time history at various points in the wall?" This problem is distinguished by the fact that no part of the circuit remains for long times at elevated

the equipment have several ranges. Thus the instruments can be used largely in the upper part of the scale, where the percentage error is smaller.

In addition to the objective errors there are those subjective ones due to inaccurate reading. The danger from this type of inaccuracy is of course increased by the fact that transients are to be observed, and therefore observations must be made while the needles of the instruments are moving more or less swiftly.

Finally, if changing initial conditions at the surface have to be represented—for instance, change of heat flow or temperature—the manual adjustment

zero the resistance is zero and gradually increases to infinity when the current is zero. When Figure 1a is considered, it becomes evident that the relative importance of the leakage changes greatly with the state of loading of the capacitor. In the case of the unloaded capacitor the equivalent resistance is very small; compared with this very small resistance the parallel leakage resistance, which is

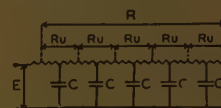


Figure 2. Equivalent circuit of a cable or of a semi-infinite wall

C —Capacitance
 R_u —Useful resistance per lump
 R —Total useful resistance
 E —Over-all voltage

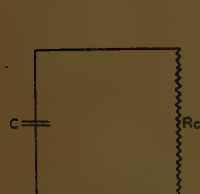


Figure 1. Equivalent circuit of a capacitor

C —Capacitance
 R_c —Leakage resistance

Figure 1a. Equivalent circuit of a capacitor
 Capacitance replaced by a variable resistance, to be changed according to voltage change of capacitance



potentials, and that the potential at the ends of the circuit remains constant. There are important thermal problems the analogous circuits of which do not show these conditions.

In the following presentation electrical units will be used; reference to equivalent heat units will be added as necessary.

II. Sources of Inaccuracy

In any type of problem to be solved on the analyzer, three sources of inaccuracy occur. They are listed here briefly, and the two which are inherent to the method are discussed individually in parts III and IV, as indicated in the list:

1. Inaccuracy due to leakage and stray currents (part III).
2. Inaccuracy due to lumping (part IV).
3. Inaccuracy in the instruments and in providing the given initial conditions.

The third group of inaccuracies is of course not inherent to this type of circuit. Neither, as far as the thermal aspect is concerned, is it inherent to the analogy method because the same type of errors would occur in measurements made and instruments used in direct thermal measurements. The objective error of the electric instruments used in the analyzer is between 0.3 and 0.5 per cent of the full-scale reading; the proportional error is therefore larger if the instruments are used on the lower part of their scales. In order to safeguard accuracy all measuring instruments in

of the power supply to this condition may cause additional inaccuracies.

III. Inaccuracy Due to Leakage and Stray Currents

Two causes of inaccuracy have to be considered here: leakage in the capacitors and stray or leakage current in the insulating parts of the circuit. It will be shown later that the two causes can be considered together. But first they will be discussed separately.

1. CAPACITIVE LEAKAGE

The capacitors which are used for representing the thermal capacity draw a leakage current after being loaded and, if left undisturbed, gradually discharge through their leakage resistance. If the capacitors were "ideal," they would draw no leakage current after being charged and would keep their charge indefinitely. In order to determine the inaccuracies introduced by the use of actual capacitors, a series of tests was conducted in which the results obtained from circuits with "ideal" capacitors were compared with the results from circuits with actual capacitors.

It is hard to obtain capacitors with specified leakage, and impossible to obtain ideal capacitors. Therefore, the capacitor, which has an equivalent circuit shown in Figure 1, is replaced by two parallel resistors, shown in the equivalent circuit, Figure 1a. The variable resistor represents the capacitance. At time

very high, can be neglected. As loading proceeds, the apparent resistance of the capacitor becomes larger, and thus the relative importance of the leakage resistance increases.

From these considerations it becomes evident that it is sufficient to investigate the steady state, that is, the condition with capacitors loaded to their steady-state potential. If in this case the leakage through the capacitor is within tolerable limits, then it is even more within these limits while the capacitor is at a lower voltage and drawing a heavier current.

Figure 2 shows the type of circuit which is to be investigated. R_u are the "useful" resistors, C the capacitors. It

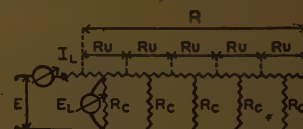


Figure 3. Circuit diagram for investigation of capacitance leakage in circuit Figure 2—steady state

R_c —Resistances equivalent to the leakage of capacitors
 R_u —Useful resistance per lump
 R —Total resistance
 I_L —Current with leaking capacitors
 E_L —Voltage with leaking capacitors
 E —Over-all voltage

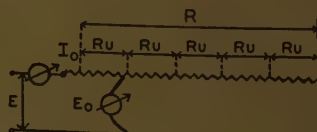


Figure 4. Circuit diagram. Nonleaking capacitors—steady state

E, R, R_u —Same meaning as in Figure 3
 E_o —Voltage } with nonleaking "ideal"
 I_o —Current } capacitors

is assumed that all sections are equal. This circuit is represented in steady state by the circuit (Figure 3) for actual—leaking—capacitors and by the circuit (Figure 4) for ideal—nonleaking—capacitors.

As mentioned previously, the investigations are carried out by comparing the results from the circuit shown in Figure 3 with those from the circuit shown in Figure 4. Two quantities are of interest in the investigations covered by this paper: voltage and current. On the electric analyzer these represent temperatures and rate of heat flow.

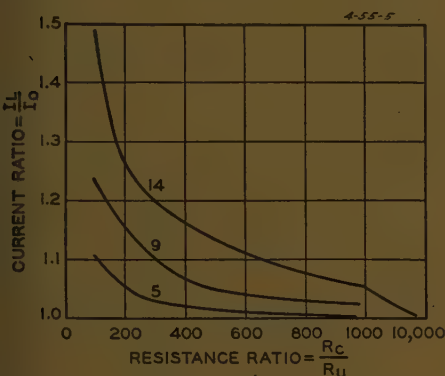


Figure 5. Current ratio, I_L/I_0 , plotted as function of the resistance ratio, R_c/R_u . The numbers on the curves (14, 9, 5) indicate the number of sections involved

I_L —Current with leakage (Figure 3)
 I_0 —Current with no leakage (Figure 4)
 R_c —Leakage resistance of capacitance
 R_u —Useful resistance per lump

Let the insulation characteristic of the capacitor be expressed by τ . In symbols this would be written as $\tau = R_c C$. τ , which is called the capacitive time constant, has the dimensions of time; thus, if R_c is given in megohms and C in microfarads, τ will be in seconds.

The leakage resistance, R_c , of any capacitor can be expressed by:

$$R_c = \tau / C \text{ megohms} \quad (1)$$

For capacitors of equal quality, the larger the capacitor the smaller will be its leakage resistance.

The product $R_u C$ for each section is the section time constant. Let this time constant be T . Then

$$T = R_u C \quad (2)$$

By comparing equation 1 with equation 2 it can be seen that R_c/R_u and therefore I_L/I_0 and E_L/E_0 do not depend on the value of C . Thus:

$$\tau / T = R_c C / R_u C = R_c / R_u \quad (3)$$

Let I_L be the current obtained for any given voltage in the circuit of Figure

3 and I_0 the current obtained with the same voltage in the circuit of Figure 4. The ratio I_L/I_0 of the two currents is plotted in Figure 5. This ratio depends on the relative value of R_c and R_u and on the number of sections. R_c/R_u is shown on the abscissa. Three curves are plotted; these are marked 14, 9, and 5, indicating the number of sections to which the curve refers. The larger the number of sections, the greater will be the current ratio I_L/I_0 and the more inaccurate will the method become. As R_c/R_u increases, the ratio I_L/I_0 decreases and approaches unity as R_c/R_u approaches infinity.

Example: Let the capacitor time constant $\tau = 50,000$ megohms $\times \mu f$ ($= 50,000$ seconds). Let each section have a resistance R_u of 0.9 megohm and a capacitance of $55.5 \mu f$. Section time constant T is $T = 0.9 \times 55.5 = 50$ megohms $\times \mu f = 50$ seconds $\tau / T = 50,000 / 50 = 1,000$. The current ratio I_L/I_0 for 14 sections is then 1.055 (from Figure 5).

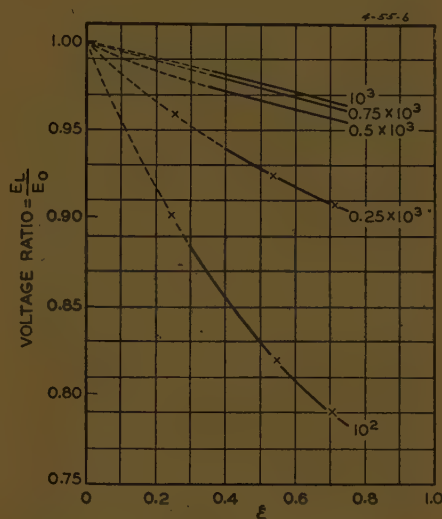


Figure 6. Voltage ratio, E_L/E_0 , plotted against fractional resistance

($\xi = 0.5$ is, for example, the center of the resistance.) 14 sections. The figures on the curves (10^3 , 0.5×10^3 , and so forth) indicate the resistance ratio, R_c/R_u . The xs show points taken with nonuniform subdivision

In Figure 6 the voltages, E_L and E_0 of the same circuits are compared. The ratio of these voltages is different at various distances from the beginning of the circuits. On the abscissa the fraction of the total resistance R is plotted (see Figure 2). For example, $\xi = 0.5$ indicates the center of the total resistance. On the ordinate the voltage ratio, E_L/E_0 is plotted. E_L/E_0 is the ratio of the voltage obtained at any one point from circuit Figure 4 to that obtained at the same point from circuit Figure 3. The total number of sections was 14.

The various curves refer to different resistance ratios R_c/R_u .

Figures 7 and 8 are similar to Figure 6 with the difference that in Figure 7 the total number of sections was nine and, in Figure 8, the total number of sections was five.

The same results are obtained in any experiments of this type (with ideal equipment) as long as T remains unchanged (see equation 2). The same results are obtained with large capacitors and small resistors as with small capacitors and large resistors. Equation 3 shows that the introduction of capacitor leakage does not modify this statement. Even with leaking capacitors the same accuracy or, of course, the same error, is reached with any value of T , independent of the distribution of T between resistance and capacitance. From this viewpoint, it becomes obvious that it is desirable to work with as few sections as possible, as may also be found qualitatively from consideration of the circuit of Figure 3.

It may be noted here that the requirements resulting from the investigations of

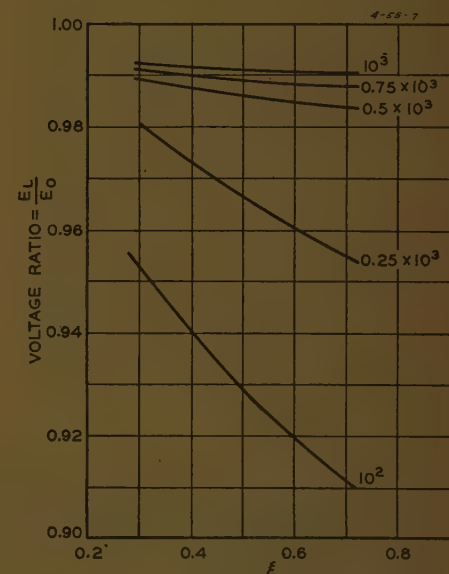


Figure 7. Voltage ratio, E_L/E_0 , against fractional resistance

(For example, $\xi = 0.5$ is the center of the resistance.) Nine sections. The figures on the curves (10^3 , 0.5×10^3 , and so forth) indicate the resistance ratio, R_c/R_u

part IV are in the opposite direction, calling for many sections.

2. EQUIPMENT LEAKAGE (OTHER THAN CAPACITIVE LEAKAGE)

So far it has been assumed that the equipment other than capacitors is free from leakage. Figure 9 shows part of the

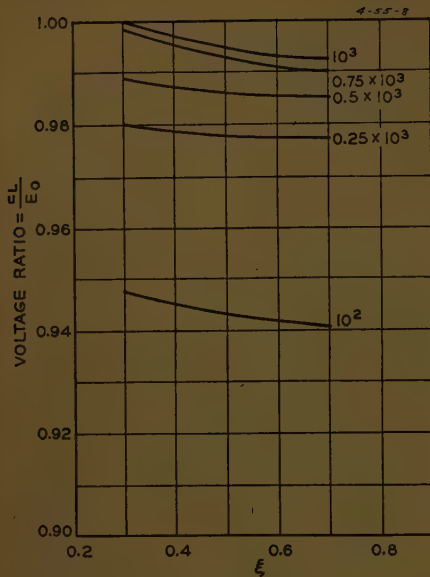


Figure 8. Voltage ratio, E_L/E_0 , against fractional resistance

(For example, $\xi=0.5$ is the center of the resistance.) Five sections. The figures on the curves (10^3 , 0.5×10^3 , and so forth) indicate the resistance ratio, R_c/R_u

laboratory equipment. It is obvious that many leaks do occur—for example, in the insulating panels on which the resistors are mounted, or in the busses which are used to connect various parts of the equipment. Although special care has been taken in the design to get as small a leakage as possible, the leakage current still is finite. In this equipment, two types of undesired currents are flowing. One, which might be called leakage, is a current flowing from any given point in the equipment to ground. The other is stray current flowing from one part of the equipment to another part which is at a different potential.

The leakage current in the insulating part may be thought of as an additional current in the capacitor. The equipment leakage (not capacitor leakage) in each section may be thought of as being replaced by one leakage resistor R_B which is parallel to the leakage resistor R_c of the capacitor. The equivalent total leakage resistance per section R_L is to be found from $1/R_L = 1/R_c + 1/R_B$ (see Figure 10).

The value of R_B changes with temperature and atmospheric conditions. In dry conditions, and, with all sections connected, it amounts on the Columbia analyzer to approximately 150 megohms. R_B is of course independent of the capacitance and also of the time constant T of the section. Therefore equation 3 does not hold if equipment leakage is to be considered. It makes considerable difference how $T-R_uC$ is divided between capacitance C and resistance R_u . The influence of R_B on R_L is smaller if R_c is smaller; moreover small R_c means, with unchanged value of T , smaller values of R_u . Therefore, from the standpoint of leakage, it is desirable to work with as high a capacitance, and consequently as low a resistance, as possible.

Example: Let $T=60$; $\tau=50,000$; $R_B=3,000$ megohms; 14 sections.

Table II shows the values of R_L/R_u and of I_L/I_0 for various possible combinations of R_u and C which yield the same $T(=60)$.

Fortunately the stray currents from one section of the circuit to another are so

Figure 9. General view of the electrical apparatus used in solving problems in three-dimensional heat flow by electrical analogy

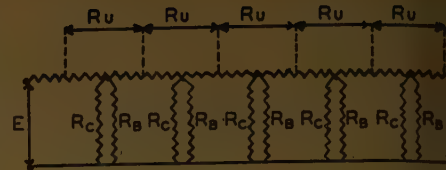


Figure 10. Equivalent-circuit leaking capacitors and leaking boards

R_u —Useful resistance
 R_c —Leakage resistance of capacitors
 R_B —Leakage resistance of board
 E —Over-all voltage

small that they can be neglected here. If they would be larger, the following reasoning would apply: A stray current from one section to the next acts like a shunt for resistor R_u . A total resistance R_u' would result with $R_u' < R_u$. If all other conditions are unchanged, the ratio R_u'/R_c would increase. However, the circuits of Figures 5 to 8 would not apply, because they are based on the assumption that R_u has the correct value, while under consideration of stray currents R_u' would be smaller than the correct value of R_u . A number of graphs would have to be determined, each holding for one ratio of R_u/R_u' .

So far it has been assumed that all sections are of equal resistance. In the thermal problem this would mean that all sections are of equal thickness. It is of course possible to make nonuniform lumps. If, for example, a circuit with a total resistance of 1.2 megohms (equivalent perhaps to a wall 12 inches thick) has to be investigated, and 12 sections or lumps are available, it is possible either to make 12 lumps, each with a resistance of 0.12 megohm (one inch thick), or to make the first three or four lumps with a resistance of only 0.06 megohm each (one half inch thick) and increase the resistance (thickness) of the others accordingly, so as to again cover the entire resistance (thickness) of 1.2 megohms (12 inches). Any other distribution would also be possible. One case was investigated: that of three small sections at the beginning of the circuit and ten large sections at the end of the circuit. Each of the three small sections at the beginning of the circuit has one third of

Table II

C	R_u	R_c	R_L	R_L/R_u	I_L/I_0
150...	0.40	333...	300...	750...	1.083
120...	0.50	416...	365...	730...	1.086
90...	0.667...	555...	470...	705...	1.090
60...	1.0	833...	652...	652...	1.098
30...	2.0	1,667...	1,075...	538...	1.122
15...	4.0	3,333...	1,580...	395...	1.160

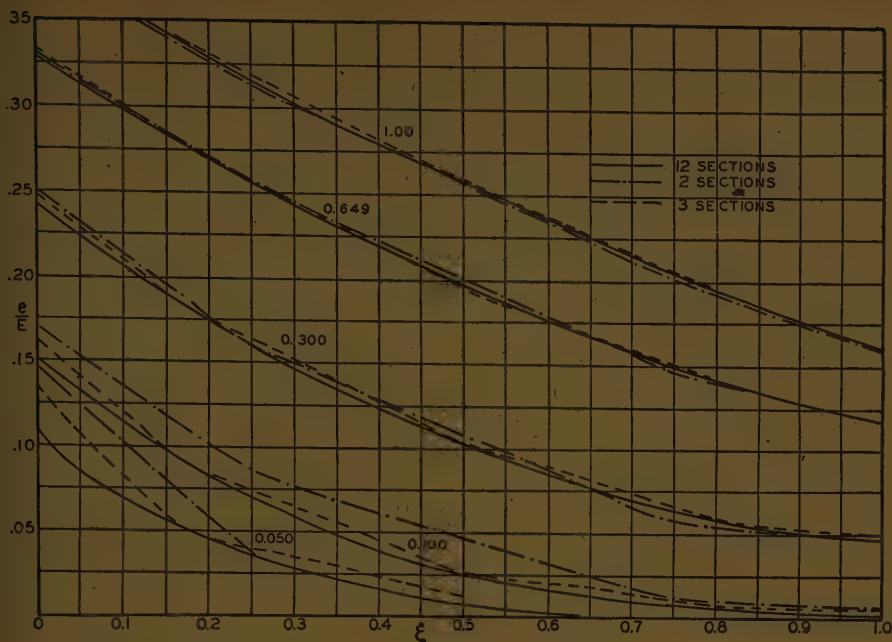


Figure 11. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h=2$, $m_c=1$. The figures on the curves indicate the dimensionless time, t/RC_t .

the resistance and one third of the capacitance of the later sections. (The one-third resistance and capacitance correspond to one-third section thickness.) The results were compared with those of a uniform circuit of the same time constant. Two cases were investigated: one for $R_c/R_u=100$, the other for $R_c/R_u=250$. (R_c/R_u referring in both cases to one lump in the uniformly subdivided circuit.) The ratios I_L/I_o for evenly distributed sections were 1.49 ($R_c/R_u=100$) and 1.22 ($R_c/R_u=250$), respectively; the corresponding values for uneven lumps or sections were 1.48 and 1.21, respectively. The measured points for the temperatures are indicated in Figure 6 (by x).

All the circuits shown so far have been based on the assumption of zero film resistance on both the hot and cold surfaces. In this connection a word of explanation is necessary. The heat exchange between a hot surface and the cooler ambient is generally characterized by a "film conductance" value (expressed, for example, in Btu per hour, square foot, degrees Fahrenheit). The underlying concept is that the heat exchange, following Newton's law, is proportional to the temperature difference between the surface and the surrounding. Although in many instances this proportionality does not exist, the introduction of a film conductance value is helpful.

In electrical terms, film conductance is represented by a noncapacitive resistance at the end of the circuit. Circuits having zero film resistances were chosen because they illustrate the worst possible conditions for accuracy. If the film resistances are not zero, then additional resistors have to be added: one on the "hot end" of the circuit, representing the film resistance of the hot surface, and one on the "cold end" of the circuit, representing the film resistance of the cold surface. If such additional resistances were applied, the voltage drop in that part of the circuit which represents the wall would be only a part of the total voltage drop. As a result, the ratio of the current with capacitors to that without capacitors would become smaller.

IV. Inaccuracy Due to Lumping

1. CONCEPT

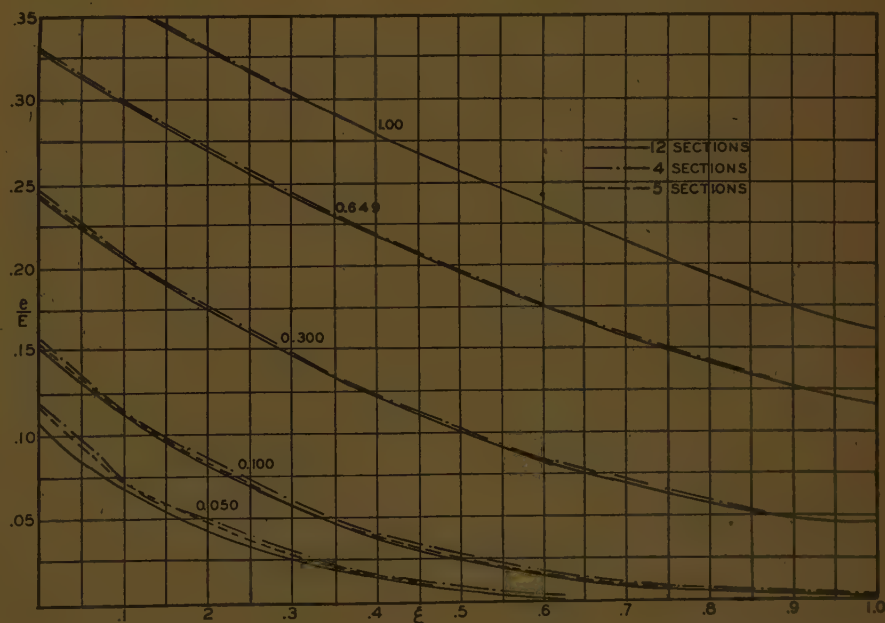
One could conceive as a theoretical limit of an equipment without any leakage, either in the capacitors or in the panels. None of the errors discussed in part III would occur, and yet the equipment would yield only approximate answers because of the errors due to lumping.

The selection of a finite number of lumps or sections instead of an infinite number is, mathematically speaking, equivalent to replacing a differential equation by an equation of finite differences. The main points of interest in this connection are the voltages, corresponding to the temperatures during the gradual heating up. In steady state the voltage-space distribution is theoretically a straight line; the actually measured points all fall on this line, independent of the number of sections used. During the heating-up period, however, more or less important discrepancies between the theoretical result and that obtained with only a few sections will occur.

In order to investigate the influence of the number of sections on the accuracy—from the viewpoint of "lumping"—it is necessary to know the theoretical curves of temperature rise. Such curves are not yet available; therefore, the curves obtained from tests in which 12 sections

Figure 12. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h=2$, $m_c=1$. The figures on the curves indicate the dimensionless time, t/RC_t .



were used were considered to be sufficiently close to the theoretical value. This assumption is upheld by past experiments and also by the fact that no measured differences were observed between the curves taken with 15 and those with 12 lumps.

2. PROCEDURE

The procedure for determining the influence of sectioning was as follows: the

as in Figure 6. The thermal parallel is, of course, fractional thickness and fractional temperature. Values of time as well as of resistance are plotted in dimensionless units. The dimensionless unit for time is t/RC_i and that for resistance or depth is $\xi=r/R=x/L$. Here t indicates the time in seconds after start of the experiment; R (as in part III) the total resistance in megohms; C_i the total capacitance in microfarads; r , in meg-

ductances," which are represented in the electrical problem by resistances without capacitance, have to be introduced. It appeared probable that the surface film conductance would have some influence on the errors caused by lumping. A preliminary investigation proved that this is the case and that worst conditions prevail for zero film resistance on both the hot and the cold surfaces. The film resistance in this connection is best expressed in dimensionless units by comparing the film resistance ($1/h$) with the thermal resistance of the wall. In the electrical analogy the resistance representing the film ($1/h$) is to be compared with the total resistance R of the circuit. The ratio of film-resistance to wall resistance is called the relative film resistance m . Symbolically, this is expressed by $m=1/hR$, where $1/h$ is converted to ohmic units.

In extreme cases the wall can be of metal with high thermal conductivity and the ambient can be still air. In such cases the value of m can rise quite high, say to more than 1,000. With so high an m the temperature difference between hot and cold surface of the piece is at any time so small that the number of sections used has no measurable influence. In fact measurable differences occur only at fairly low values of m . Therefore, a series of tests was run, gradually increasing the values of m , that is, increasing the hot- and cold-surface relative film resistances. It was found that beyond $m_h=6$ no appreciable voltage (temperature) differences occur within the circuit. Even for values of m in the order of magnitude of two the differences are not large. This can be seen by comparing Figures 11 and 12 with Figures 13 and 14. Figures 11 and 12 refer to $m_h=2$, $m_c=1$, while Figures 13 and 14 refer to $m_h=m_c=0$.

In Figures 11 and 13 the results for two and three sections are compared with those for 12 sections (12 sections being assumed to be identical with the theoretical curve). In Figures 12 and 14 the results for four and five sections are compared with those for 12 sections.

By comparing the group of curves for $t/RC_i=0.100$ (Figure 13) with those for $t/RC_i=0.1026$ (Figures 13, 14) it becomes evident that the difference between the curves for few sections and those for 12 sections is smaller for large values of m . A number of experiments have been carried out using different combinations for m_h and m_c . For space economy, these cannot be reproduced here. It is sufficient to say that the differences between "many"

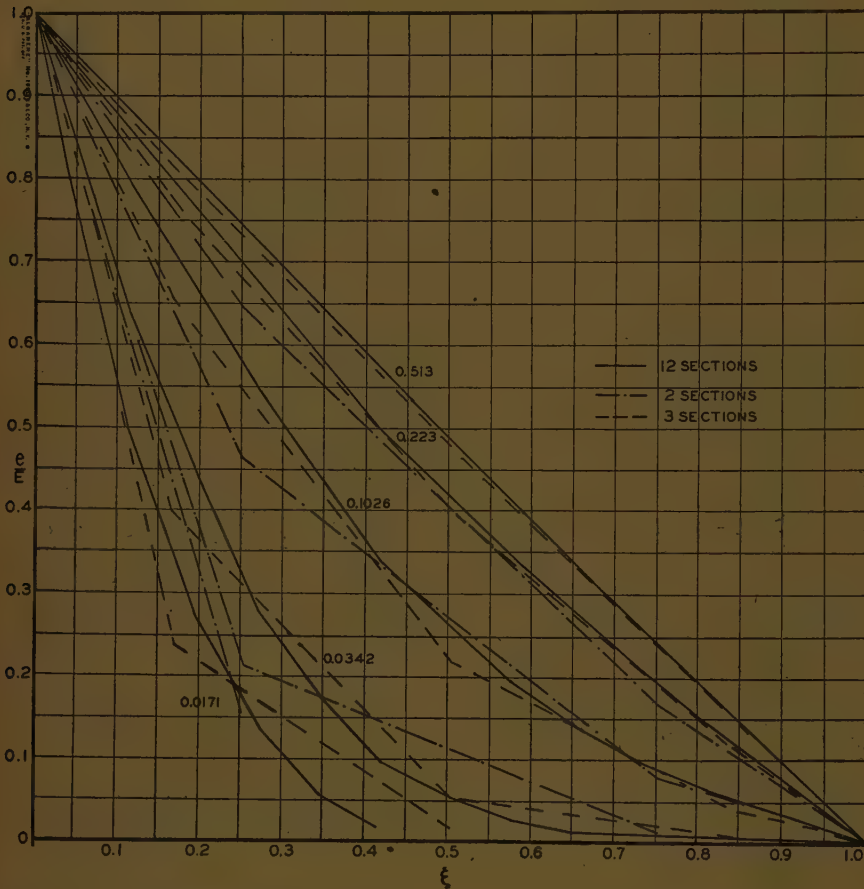


Figure 13. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h=m_c=0$. The figures on the curves indicate the dimensionless time, t/RC_i

voltage rise at various points in the circuit—equivalent to a temperature rise at various depths in the wall—were measured, using in consecutive experiments a different number of lumps. The voltages obtained for any given point in the circuit—depth in the wall—and at any given time, using small numbers of lumps, were then compared with the voltage for the same space, position, and time obtained with 12 lumps.

Figures 11 to 14 show the results of these experiments. The ratios of the voltages measured at various points in the circuit to the impressed voltage are plotted against the fraction of the total resistance,

ohms, the resistance at the point in question; x , in feet, its distance from the hot surface; and L , in feet, the thickness of the wall. (It should be noted that on these charts, total resistance and total capacitance are used, whereas in part III the resistance and capacitance per section were used.) The lines between the measured temperatures are drawn straight. On the plots shown measured temperatures are connected by straight lines, because in the case of only a few sections the proper rounding of the curves might be somewhat uncertain. It should be noted, however, that the straight lines tend to accentuate differences between the various curves.

3. FILM CONDUCTANCE

It was mentioned previously that in thermal problems "surface film con-

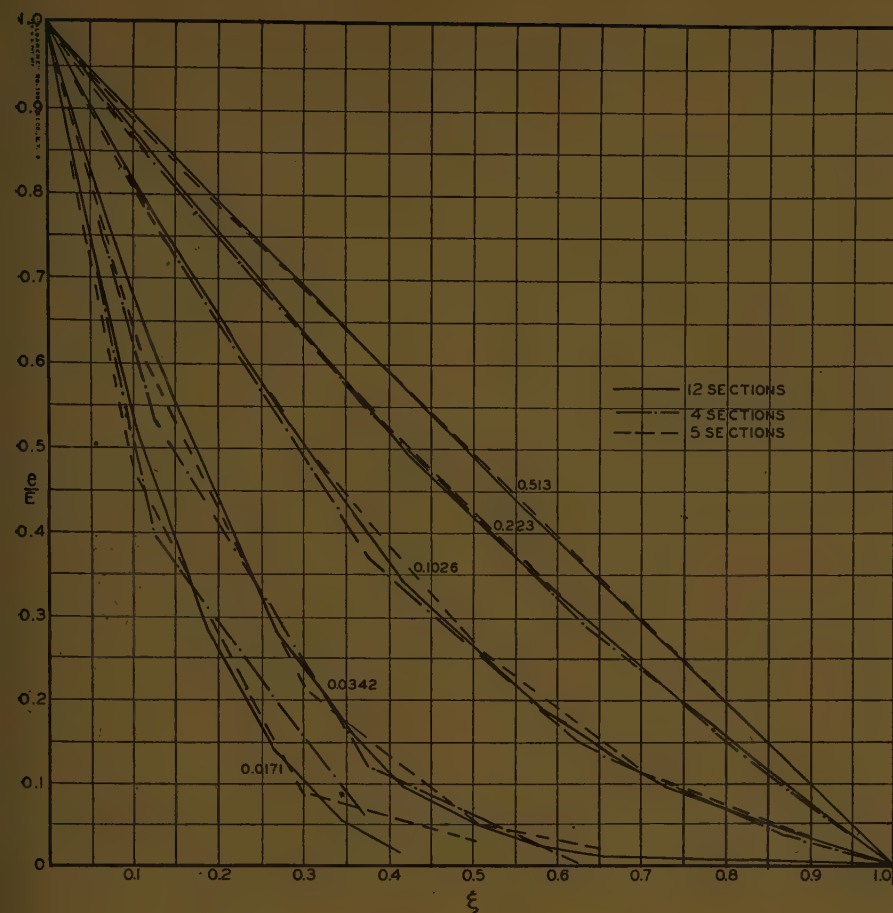


Figure 14. Voltage (temperature) rise in the circuit (wall)

Relative film resistance $m_h = m_c = 0$. The figures on the curves indicate the dimensionless time, t/RC_i .

and "few" lumps were consistently smaller for large m 's than for $m_c = m_h = 0$. Generally speaking, m_c is of smaller influence than m_h .

4. CONCLUSIONS

1. Two or three lumps are not sufficient to represent a problem except for very approximate solutions or for values of t/RC_i at or near the steady state. The steady-state or near-steady-state t/RC_i would be small for low m 's in comparison with steady-state t/RC_i for large m 's.

2. Five lumps give very good results except for relatively small values of t/RC_i .

3. In general a small number of lumps is sufficient if voltages (temperatures) at greater distance from beginning of the circuit (the hot surface) and at later times after start (that is, at higher values of t/RC_i) are necessary.

V. General Conclusions

In order to counteract the inaccuracies due to leakage, a small number of lumps is desirable. In order to counteract inaccuracies due to lumping, a large number of lumps is desirable. A practical medium is between six and nine lumps; then none of the influences become large.

The selection of nonuniform sections or lumps does not seem to influence the accuracy. Lumps can therefore be made so as to give a great number of readings in that part of the body to be investigated which is of greatest interest.

The preceding considerations hold only for the problem mentioned. Conditions may change in different types of problems, either adding resistors and capacitors to simulate two-dimensional heat flow, or in problems where parts of the circuits are kept at elevated voltages for some time.

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A Design Method for D-C Machines

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INTEREST in d-c machines in many phases of the war effort prompts the writers to present a method of design which has been found to be very useful and time saving. The method makes use of fundamental relationships in somewhat different forms and approaches the design from a different viewpoint than is ordinarily the case. The procedure has been in use for some time in the design of low-voltage aircraft motors and normal-voltage integral horsepower motors and generators. Comparative design and test results have shown good agreement.

The most common type of design problem is one which makes use of standard mechanical parts from which the required performance is realized by proper proportioning of the windings. Even though the rating required is a rather unusual one, it is rarely economically feasible to make a complete new design, mechanically and electrically. Or, if a new mechanical design is made, future requirements will make it necessary to use the same frame for other ratings.

If the mechanical design is fixed, dimensional details of the magnetic circuit (with the possible exception of stacking) are known, and the magnetization curve and rotational losses become known or can be calculated by conventional methods.

While the design method is developed and illustrated herewith for a series motor with commutating poles, the principles are applicable and can be extended easily to include shunt and compound machines.

Design Considerations

In the conventional design of a d-c motor, when the magnetization curve is given, the usual procedure is to select an operating point on the curve, thereby fixing the flux. On assuming a value of generated voltage, it is then possible to calculate the number of series conductors required in the armature winding. In order to check the performance of the machine, it is necessary to make a further assumption of armature current; this in reality involves an assumption of machine efficiency. As will be demonstrated later, the selection of an operating point on the magnetization curve fixed the ratio of field ampere-turns to armature ampere-

turns per pole. It is a well-known fact that this ratio has an important bearing on commutation, iron losses, and distribution of copper losses, hence, heating in the field and armature. Thus, it is proposed to select this ratio at the outset, thereby fixing the operating point on the magnetization curve for a given full-load output (see Appendix I). At the same time the selection of a ratio of field-to-armature ampere-turns establishes the series-field turns per pole in terms of the armature turns per coil. The commutating-pole turns per pole also can be written in terms of armature turns per coil. Expressions for these winding ratios F_w and F_{wc} , respectively, are developed in Appendix II.

In a d-c motor the applied voltage minus the brush-contact drop must be balanced by the generated voltage plus the voltage drop in the series windings and armature. Thus

$$V - V_{BR} = E + I_a R_o \quad (1)$$

The generated voltage is

$$E = \left(\frac{2\phi P S_c \text{ rpm}}{a \times 60 \times 10^8} \right) T = BT \quad (2)$$

This is the usual form of the voltage equation, except that the total number of armature conductors has been replaced by its equivalent in terms of armature turns per coil (T) and commutator segments (S_c). As indicated in equation 2, E is dependent only on T , since the flux is already determined by selection of the operating point on the magnetization curve as discussed previously.

The series voltage drop is

$$I_a R_o = I_a (R_a + R_F + R_{cp}) \quad (3)$$

It is shown in Appendix III that the armature resistance (R_a) is a function of T^2 and that, when making use of the winding ratios, F_w and F_{wc} , the resistances of the series-field and commutating-pole windings are also functions of T^2 .

Equation 3 then can be written

$$\begin{aligned} I_a R_o &= I_a r_o T^2 \\ &= (I_a T r_o) T \\ &= \left[\frac{(NI)_F}{F_w} \right] r_o T \\ &= C r_o T \end{aligned} \quad (4)$$

C becomes known upon selection of the operating point on the magnetization

curve, and r_o is essentially a constant for a given frame. An expression for r_o is developed in Appendix III. It is important to note that, having fixed reasonable values for F_w and F_{wc} , r_o is a constant, independent of the winding and machine rating.

It is now apparent that equation 1, with the values for E and $I_a R_o$ from equations 2 and 4 substituted, can be solved for T , the required armature turns per coil. Thus

$$T = \frac{V - V_{BR}}{B + C r_o} \quad (5)$$

Also, if the winding ratios are used, the number of series-field turns per coil is $F_w T$ and the number of commutating-pole turns per coil is $F_{wc} T$. Since the useful copper areas for each field winding and the armature are also known, conductor sizes can be determined. Furthermore, the armature current can be calculated as

$$I_a = C/T \quad (6)$$

Since the winding as well as the full-load current are known now, the complete performance of the motor can be calculated. Details of calculation are illustrated in the sample design.

In conclusion, the foregoing information has proved useful in instances where the design problem involves determination of winding details and performance when the mechanical design is fixed. The method involves no new fundamental theory but yields a design directly wherein certain important factors are incorporated in such a way as to insure their ultimate realization in the performance of the machine. In addition, calculated performance will be in general in much better agreement with test results than is the case in conventional methods.

Appendix I. Determination of Operating Point on Magnetization Curve

It is assumed that the open-circuit magnetization curve and rotational-loss data, such as are shown in Figure 1, are known from test of previous designs in the particular frame in question or have been calculated by conventional methods.

The power developed in the armature of a

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c machine is $E I_a$ and must equal the power output (W) plus the rotational loss (RL). The latter includes core losses as well as friction and windage and stray load loss. Thus

$$W' = W + RL = E I_a \quad (7)$$

out

$$E = \frac{\phi P Z \text{ rpm}}{a \times 60 \times 10^8} \quad (8)$$

hence

$$W' = \frac{\phi P \text{ rpm } Z I_a}{a \times 60 \times 10^8} \quad (9)$$

The armature ampere-turns per pole, $(NI)_a$, are equal to $Z I_a / 2aP$. Equation 9 then may be written

$$W' = \frac{\phi P^2 \text{ rpm}}{3 \times 10^9} \times (NI)_a \quad (10)$$

It is desired to use the ratio of field ampere-turns to armature ampere-turns per pole, γ , as a starting point in the design. Hence, if $(NI)_a$ in equation 10 is replaced by $\gamma / (NI)_F$ and if terms are rearranged

$$\phi (NI)_F = \frac{W'}{\text{rpm}} \times \frac{\gamma}{P^2} \times 3 \times 10^9 = A \quad (11)$$

Thus, the operating point on the magnetization curve is fixed by the output of the machine, speed, number of poles, and the ampere-turn ratio. The choice of a suitable value for γ for a given design will depend on the type of machine and the application. The range is usually from 0.6 for series machines to 1.25 for shunt machines. A good average value for shunt or compound machines with commutating poles is 1.0.

Every point on the magnetization curve corresponds to a certain value of $\phi \times (NI)_F$. A particular value is required to meet the rating requirements. One obvious method for determining the operating point would be to plot a curve of $A = \phi (NI)_F$ versus $(NI)_F$ and read from this curve the value of $(NI)_F$ for the particular value of A which is required. In obtaining such a curve, the full-load magnetization curve should be used.

The flux per pole (ϕ) in equation 11 is the full-load value and will be less than that obtained from the no-load curve for given field excitation due to the demagnetizing effects of armature reaction. If the brushes are shifted from the no-load neutral, the direct demagnetizing ampere-turns of the armature are

$$(NI)_{dm} = \frac{\theta}{90} (NI)_a = \frac{\theta}{90} \frac{(NI)_F}{F_w} \quad (12)$$

Various methods are available for determining the demagnetizing effect of the cross-magnetizing ampere-turns, most of which are quite tedious to apply and not well adapted for use in a design method such as this. For small machines, a simple expression

$$(NI)_{dcm} = \frac{1.1 (NI)_F^2}{10^4 F_w} \quad (13)$$

has been found to give quite satisfactory results. If equations 12 and 13 and the no-load magnetization curve are used, it is

possible to construct full-load magnetization curves for any given values of θ and γ . However, as illustrated later in the sample design, there is little need for obtaining the full-load curve, since the required point on the curve can be calculated rather easily.

Appendix II. Winding Ratios, F_w and F_{wc}

The winding ratios F_w and F_{wc} are defined as the ratios of series-field turns per pole to armature turns per coil and commutating-pole turns per pole to armature turns per coil, respectively. Thus, F_w is equal to N_f/T and F_{wc} is equal to N_{cp}/T . An expression for F_w can be found in terms of known quantities from the definition of γ as

$$\gamma = \frac{(NI)_F}{(NI)_a} = \frac{N_f I_a}{Z I_a} = \frac{aP}{S_c} \frac{N_f}{T} \quad (14)$$

or

$$\frac{N_f}{T} = F_w = \frac{\gamma S_c}{aP} \quad (15)$$

In a similar manner, F_{wc} is found to be

$$F_{wc} = \frac{N_{cp}}{T} = \frac{\sigma S_c}{aP} \quad (16)$$

Where σ is the ratio of commutating-pole ampere-turns per pole to armature ampere-

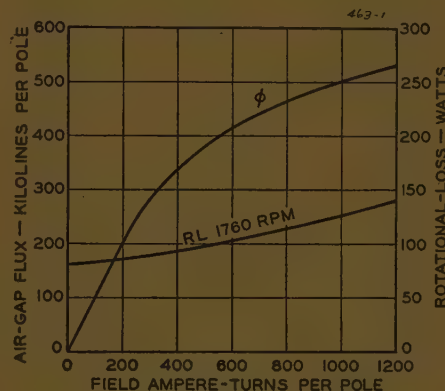


Figure 1. Magnetization and rotational-loss curves

turns per pole. A common value for σ is about 1.25.

Appendix III. Resistances in Terms of T

(a). Armature resistance, R_a .

The usual expression for the resistance of the armature at 25 degrees centigrade, in terms of resistivity, number of series conductors, and cross-section area of each, is

$$R_a = \frac{0.880 l_a Z}{C M_{sa} a^2} \text{ ohms} \quad (17)$$

If Z is written in terms of T and the number of commutator segments, and the area of each conductor is replaced by the

useful slot area divided by the number of conductors per slot, equation 17 becomes

$$R_a = \frac{0.880 l_a (2 S_c T)}{\left(\frac{S_s C M_{sa}}{2 S_c T} \right) a^2} = \left[\frac{3.52 l_a S_c^2}{S_s C M_{sa} a^2} \right] T^2 \text{ ohms} \quad (18)$$

(b). Series-field resistance, R_F .

The series-field resistance at 25 degrees centigrade is

$$R_F = \frac{0.880 l_F N_F P}{C M_F} \text{ ohms} \quad (19)$$

Again the area of each conductor is replaced by an expression involving the useful copper area for the field winding, and $F_w T$ is substituted for N_F . Then

$$R_F = \frac{0.880 l_F P (F_w T)}{C M_{SF} / F_w T} = \left[\frac{0.880 l_F P F_w^2}{C M_{SF}} \right] T^2 \text{ ohms} \quad (20)$$

(c). Commutating-pole-winding resistance, R_{cp} .

The resistance of the commutating-pole windings at 25 degrees centigrade is

$$R_{cp} = \frac{0.880 l_{cp} N_{cp} P_c}{C M_{cp}} \text{ ohms} \quad (21)$$

When similar substitutions are made to those suggested in b, equation 19 becomes

$$R_{cp} = \left[\frac{0.880 l_{cp} P_c F_{wc}^2}{C M_{sc}} \right] T^2 \quad (22)$$

The summation of equations 18, 20, and 22 is the total series-winding resistance of the machine at 25 degrees centigrade, R_o . Hence

$$R_o = R_a + R_F + R_{cp} = \left[\frac{3.52 l_a S_c^2}{S_s C M_{sa} a^2} + \frac{0.880 l_F P F_w^2}{C M_{SF}} + \frac{0.880 l_{cp} P_c F_{wc}^2}{C M_{sc}} \right] T^2 \quad (23)$$

$$= r_o T^2 \quad (24)$$

In using equation 24 a correction factor for temperature should be applied, since the expression as given is at 25 degrees centigrade.

Numerical Example

If the basic equations derived in the foregoing discussion are used, the details of a typical design will be illustrated. It is required to determine the winding and full-load performance for a 250-volt 2.0-horsepower 1,800-rpm d-c series motor in a standard National Electrical Manufacturer's Association frame 224.

The necessary mechanical details for the design, taken from previous designs in the same frame, are as follows:

- Number of main poles (P) = 2
- Number of commutating poles (P_c) = 1
- Mean length of turn in main field (l_F) = 18.0 inches
- Available copper area per coil in main field ($C M_{SF}$) = 1,400,000
- Mean length of turn in commutating-pole winding (l_{cp}) = 11.5 inches

Available copper area per coil in commutating-pole winding (CM_{sc}) = 1,000,000 circular mils

Number of armature slots (S_a) = 29

Number of commutator segments (S_c) = 58

Mean length of armature conductor (l_a) = 8.50 inches

Available copper area per slot CM_{sa} = 100,000 circular mils

The open-circuit magnetization curve and rotational-loss data for this particular frame are given in Figure 1.

From the rotational-loss curve, a preliminary estimate of rotational loss for this motor is made as 130 watts. The output is 2.0 horsepower or 1,492 watts. Thus, when equation 7 is used

$$W' = W + RL = 1,492 + 130 = 1,622 \text{ watts}$$

Next, a suitable value of the ampere-turn ratio (γ) is chosen as 0.87. Then, if equation 11 is used

$$A = \frac{W'}{\text{rpm}} \times \frac{\gamma}{P^2} \times 3 \times 10^9$$

$$= \frac{1,622}{1,800} \times \frac{0.87}{4} \times 3 \times 10^9$$

$$= 0.588 \times 10^9 = \phi \times (NI)_F$$

If the material following equation 11 is kept in mind, the full-load flux per pole (ϕ) and full-load ampere-turns per pole in the field ($(NI)_F$) can be determined now. The full-load magnetization curve will be somewhat below that shown in Figure 1 and approximately 1,100 ampere-turns will be required to produce a flux per pole of 520,000 lines. The product of these two figures is essentially the required value of A .

To determine demagnetizing ampere-turns it is necessary to consider only the demagnetizing effect of the cross-armature ampere-turns, since the angle of brush shift θ is zero. Thus, from equation 13 the demagnetizing ampere-turns per pole are $1.1 \times (1,100)^2 / 0.87 \times 10^{-4}$ or 153. Subtracting this from the original value of $(NI)_F$ gives 950 ampere-turns, and the corresponding value of flux from the magnetization curve is 495,000. But $1,100 \times 495,000$ does not equal 0.588×10^9 , and it is apparent that $(NI)_F$ must be increased. Let the gross field ampere-turns be 1,170. Then the demagnetizing ampere-turns are 160, the net field excitation is 1,010 and the flux is 503,000. The product of 1,170 and 503,000 gives the required value for A . Thus, the full-load operating point on the magnetization curve has been fixed. Now the preliminary estimate of rotational loss can be revised on the basis of a more accurate knowledge of the field ampere-turns, and the aforementioned process can be repeated if more accuracy is desired.

The foregoing procedure for determining the full-load flux and field excitation at first may seem rather complicated and time consuming. However, it has been found that after a little practice the operation becomes very simple and fast.

The next step is to calculate the winding ratios F_w and F_{wc} from equations 15 and 16

$$F_w = \frac{\gamma S_c}{aP} = \frac{0.87 \times 58}{2 \times 2} = 12.6$$

$$F_{wc} = \frac{\sigma S_c}{aP} = \frac{1.25 \times 58}{2 \times 2} = 18.1$$

The resistance term r_o can be determined now from equation 23

$$r_o = \frac{3.52 l_a S_c^2}{S_a CM_{sa} a^2} + \frac{0.88 l_P P F_w^2}{CM_{sf}} + \frac{0.880 l_{cp} P_c F_{wc}^2}{CM_{sc}}$$

$$= \frac{3.52 \times 8.5 \times (58)^2}{29 \times 100,000 \times 4} + \frac{0.88 \times 18 \times 2 \times (12.6)^2}{1,400,000} + \frac{0.88 \times 11.5 \times 1 \times (18.1)^2}{1,000,000} = 0.01563$$

For an average operating temperature of 65 degrees centigrade r_o is 0.018.

The constants B and C are calculated from equations 2 and 4. Thus

$$B = \frac{2\phi P S_c \text{ rpm}}{a \times 60 \times 10^8}$$

$$= \frac{2 \times 503,000 \times 2 \times 58 \times 1,800}{2 \times 60 \times 10^8} = 17.5$$

and

$$C = \frac{(NI)_F}{F_w} = \frac{1,170}{12.6} = 93.0$$

The required number of armature turns per coil is obtained from equation 5. A brush-contact drop of two volts is assumed

$$T = \frac{V - V_{BR}}{B + C r_o} = \frac{250 - 2}{17.5 + 93 \times 0.018} = 13$$

The armature current can be calculated now from equation 6.

$$I_a = \frac{C}{T} = \frac{93}{13} = 7.15 \text{ amperes}$$

The number of field turns and commutating-pole turns per pole is obtained by multiplying F_w and F_{wc} , respectively, by T . Thus

$$N_F = F_w T = 12.6 \times 13 = 164$$

and

$$N_{cp} = F_{wc} T = 18.1 \times 13 = 235$$

The required conductor size in the armature winding is obtained from the useful slot area and the number of conductors per slot

$$CM_a = \frac{CM_{sa} \times S_a}{2 S_c T} = \frac{100,000 \times 29}{2 \times 58 \times 13}$$

$$= 1,925 \text{ circular mils}$$

This wire size is between numbers 17 and 18 (American wire gauge), and a choice must be made between reducing the number of turns slightly and using number 17 or using number 18 and not filling the slot. Here the former choice is made. Thus, a $12\frac{1}{2}$ -turn winding using number 17 wire (2,048 circular mils) is adopted. The corrected number of armature conductors is

$$Z = 2 S_c T = 2 \times 58 \times 12.5 = 1,450$$

Since the value of T was reduced slightly, the series-field turns must be reduced also if the assumed value of γ is to be maintained. However, this will result in some-

what higher speed than originally assumed. Thus, again there are two alternatives, of which the former will be used. Then

$$N_F = 12.6 \times 12.5 = 160$$

and

$$N_{cp} = 18.1 \times 12.5 = 225$$

The conductor size for the series field is CM_{sf} divided by N_F and is equal to 1,400,000/160 or 8,750 circular mils.

Use three number 16 wires in parallel, giving an equivalent conductor of 7,750 circular mils. For the commutating pole use

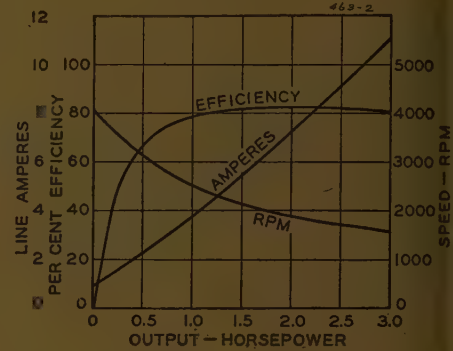


Figure 2. Performance curve for a 250-volt, 2.0-horsepower, 1,800-rpm d-c series motor

220 turns of two number 16 wires equivalent to 5,166 circular mils.

In order to check the motor performance using the aforementioned winding, the winding resistances are calculated in the usual manner

$$R_a = \frac{0.88 l_a Z}{a^2 CM_a} = \frac{0.88 \times 8.5 \times 1,450}{4 \times 2,048}$$

$$= 1.325 \text{ ohms at 25 degrees centigrade}$$

$$R_a(\text{hot}) = 1.15 \times 1.325 = 1.52 \text{ ohms}$$

$$R_{fs} = \frac{0.88 l_P N_F P}{CM_{sf}} = \frac{0.88 \times 18 \times 160 \times 2}{7,750}$$

$$= 0.645 \text{ ohm at 25 degrees centigrade}$$

$$R_{fp}(\text{hot}) = 1.15 \times 0.645 = 0.75 \text{ ohm}$$

$$R_{cp} = \frac{0.88 l_{cp} N_{cp} P_c}{CM_c} = \frac{0.88 \times 11.5 \times 220 \times 1}{5,166}$$

$$= 0.431 \text{ ohm at 25 degrees centigrade}$$

$$R_{cp}(\text{hot}) = 1.15 \times 0.431 = 0.49 \text{ ohm}$$

and the total series resistance is

$$R_o(\text{hot}) = R_a(\text{hot}) + R_{fp}(\text{hot}) + R_{cp}(\text{hot})$$

$$= 2.76 \text{ ohms}$$

For full-load armature current of 7.15 amperes, the $I_a R_o$ drop is 19.7 volts. Assuming a brush-contact drop of two volts, the generated voltage is 228.3 volts.

At this point the field ampere-turns, armature ampere-turns, and their ratio can be calculated and the full-load flux can be checked before determining the speed. Thus

$$(NI)_F = I_a N_F = 7.15 \times 160 = 1,143$$

$$(NI)_a = \frac{Z I_a}{2 a P} = \frac{1,450 \times 7.15}{2 \times 2 \times 2} = 1,297$$

Inverter Action on Reversing of Thyatron Motor Control

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Synopsis: Thyatron control of d-c motors offers a fast and smooth braking or reversal which is finding wider application in industry as the characteristics become better known.

With proper control the rectifier circuit, which normally supplies power to the armature of the motor, can be operated as an inverter to decelerate the motor by regenerating the rotational energy of the motor and its load into the a-c system. The circuit then shifts to rectifier operation to accelerate the motor and load to the preset speed in the reverse direction.

The motor-armature current can be held very nearly constant over the full reversal operation of deceleration and acceleration at a value which can be made less than the rated motor current. Test results and theory show that the motor's inherent reactance is sufficient for inverter operation, and, that during normal inversion, commutation of the tubes is not difficult.

In addition, inversion can be utilized to bring the motor to a stop more efficiently than by plugging and more rapidly and efficiently than by dynamic braking.

A GREAT many of the mechanized operations carried on in the industrial field call for a reversal of the mechanism

by its motive power which is commonly an electric motor. In nearly all cases this reversal must not impose a severe strain on the mechanism nor demand an excessive overload from the power lines. In many of these reversing drives, particularly where they are of a cyclic nature, the reversal time is lost time and must be kept to a minimum consistent with the rating of the motor. Many of these drives call for the flexibility of the d-c motor. The d-c motors are supplied commonly from either a d-c shop bus or a motor generator set. However, an increasing number of d-c-motor applications are using the thyatron-tube rectifier to give a wide range of control, including a fast and smooth reversal.

The motor in a Ward Leonard drive is

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reversed by reversing the generator voltage and the current in the loop circuit. The thyatron-tube rectifier operating a motor in some respect is comparable with the Ward Leonard drive, but it has at least one important difference. The rectifier, unlike the generator, is a unidirectional conductor. It will conduct current in only one direction. Therefore, if the rectifier output voltage is reduced, the generated voltage of the motor cannot reverse the current through the circuit. Since the current through the motor-armature circuit must be reversed to reverse the direction of the motor torque, the armature connections must be reversed mechanically with respect to the tube circuit. To reverse connect the rotating motor armature suddenly into the "full-on" rectifier would amount to plugging with short-circuit current. This would be, to say the least, highly undesirable from the standpoint of the tubes, motor commutation, and the connected load. However, by proper control the tube circuit may be made to invert the d-c power generated by the motor into the a-c lines at a controlled rate.

It is not the intent of this paper to discuss the general theory nor to state a rigorous analysis of inversion, but to give a general description of the principle of inversion operating from the generated voltage of a d-c motor into the voltage of the a-c line and some means of controlling

$$\gamma = \frac{(NI)_F}{(NI)_a} = 0.881$$

Demagnetizing ampere-turns

$$(NI)_{dem} = 1.1 \times 10^{-4} \times \frac{(1,143)^2}{0.881} = 163$$

and the net field ampere-turns, $(NI)_F$ are

The full-load flux, ϕ , is 500,000 lines per pole (from curve Figure 1). When the voltage equation is used, the speed is

$$\text{rpm} = \frac{E_a \times 60 \times 10^8}{ZP\phi} = \frac{228 \times 2 \times 60 \times 10^8}{1,450 \times 2 \times 500,000} = 1,885$$

Note that the speed is somewhat higher than originally assumed, since the $12\frac{1}{2}$ -turn armature winding was used instead of the 13-turn winding.

The power developed in the armature is EI_a or 1,633 watts, and, from Figure 1, the rotational loss is approximately 145 watts. The motor output is then 1,488 watts, the input is 1,788 watts, and the efficiency is 83 per cent.

Test results on a motor using the aforementioned winding design are shown in

Figure 2. The full-load current was 7.18 amperes, and the efficiency was 82.5 per cent. The calculated rpm was slightly high, as the test shows 1,870 rpm.

Although the winding details as shown previously are complete, it is usually desirable to check on the distribution of copper losses, current density in brushes, flux densities in various parts of the magnetic circuit, and reactance voltage of commutation.

List of Symbols

a = parallel paths in armature windings
 CM_{sa} = circular mils per slot in armature
 CM_{sc} = circular mils per coil in commutating winding
 CM_{sf} = circular mils per coil in series-field winding
 E = generated voltage in armature winding
 F_w = winding ratio (for motor)
 F_{wc} = winding ratio for commutating poles
 I_a = armature current, amperes
 I_F = field current, amperes
 l_a = mean length of armature conductor

l_F = mean length of turns in series-field coil
 l_{cp} = mean length of turn in commutating-field coil
 N_{cp} = commutating-pole turns per pole
 N_F = series-field turns per coil
 P = number of main poles
 P_c = number of commutating poles
 R_a = armature resistance
 R_{cp} = commutating-field resistance
 R_F = series-field resistance
 R_o = total series resistance
 RL = rotational losses
rpm = speed in revolutions per minute
 S_c = number of commutator segments
 S_s = number of armature slots
 T = armature turns per pole
 V = applied volts
 V_{BR} = brush-contact drop in volts
 W = machine output in watts
 γ = ratio of main-field ampere-turns per pole to armature ampere-turns per pole
 σ = ratio of commutating-field ampere-turns per pole to armature ampere-turns per pole
 ϕ = armature flux per pole

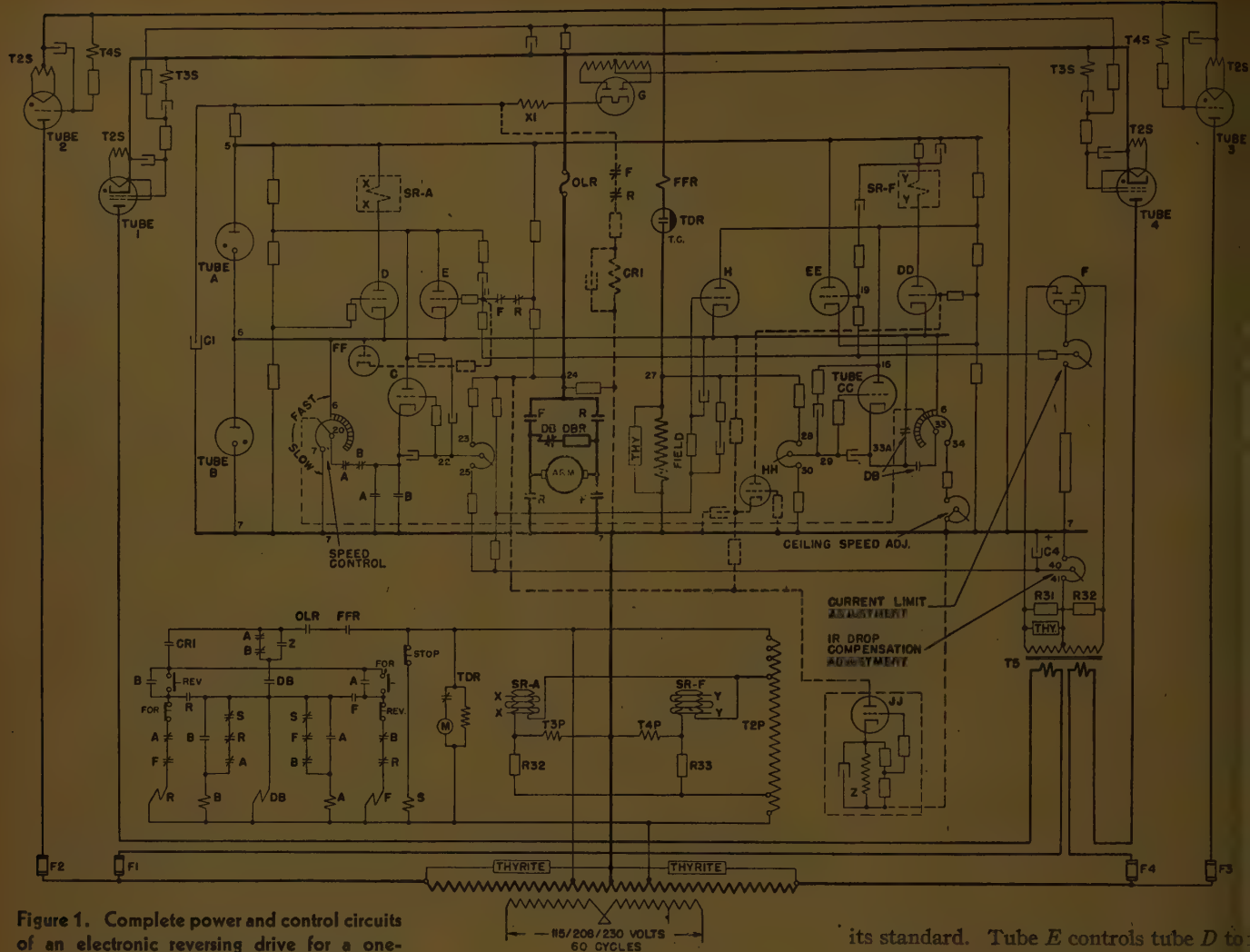


Figure 1. Complete power and control circuits of an electronic reversing drive for a one-horsepower 230-volt d-c shunt motor

this operation. Inversion is discussed from the standpoint of its usefulness in decelerating the thyatron-controlled d-c motor.

Brief Description of General Control

The method of controlling the inverter depends upon the type of rectifier circuit that is used, the method of controlling the thyatron grids, and the performance that is desired. The discussion of the circuit arrangement for the control of the inverter operation will be limited in this paper principally to one example. Since only inverter operation is to be covered here, the circuit used as an example is one the operation of which, except for inversion, was described quite thoroughly in a previous AIEE paper.¹ The complete control circuit is given in Figure 1.

Briefly, this control consists of two conventional biphas half-wave thyatron rectifiers and their associated control. Both rectifiers are operated from a single-anode transformer, one supplying the armature of the motor and the other supplying the field. The grid control of

the thyratrons is by means of saturable reactor phase-shifting bridges. A small auxiliary thermionic rectifier supplies a d-c voltage, which is held constant by a pair of voltage regulator tubes, A and B, for the operation of the control vacuum tubes and for saturating the reactors.

The saturation of the armature and field saturable reactors SR-A and SR-F is controlled by two triodes, D and DD. Two voltage-amplifier tubes, C and CC, compare a portion of the armature and field voltages with an adjustable portion of a fixed voltage used as a standard and control tubes D and DD in the proper sense to regulate the armature and field voltages in proportion to the adjustments of the standards. These adjustable standards are the two speed-control potentiometers which are ganged together and so constructed and connected that they give the proper sequence of armature and field control.

Two other voltage amplifiers, tubes E and EE, compare a voltage proportional to the motor-armature current with two other fixed standards, each operating only when this current signal rises above

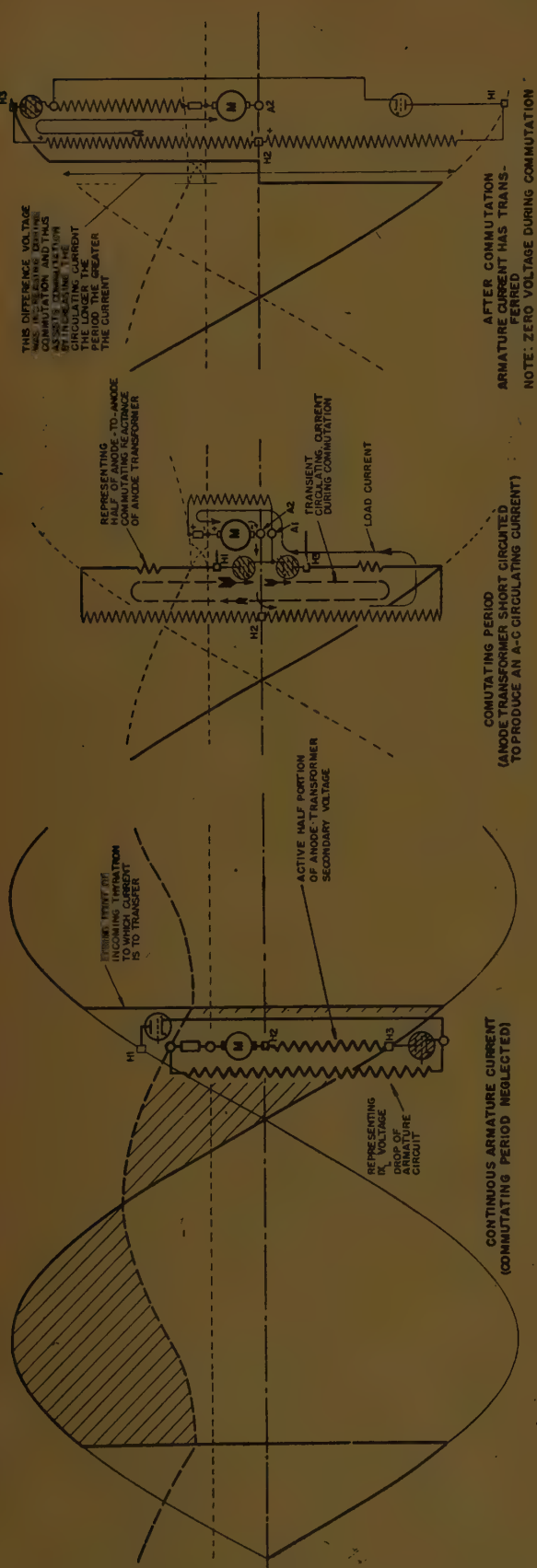
its standard. Tube E controls tube D to reduce the armature voltage. Tube EE controls tube DD to raise the field voltage, but, since the standard of tube EE is slightly lower than that of tube E, it operates at a slightly lower current signal. The results are that, on overload of the motor, the field is strengthened before the armature voltage is reduced, and that, during acceleration of the motor, the armature voltage rises to full value before the field is permitted to weaken. The voltage proportional to the armature current is obtained by rectifying the secondary voltage of a current transformer, T5, the two primaries of which are connected in the anode circuits of the two armature thyratrons. It is this part of the circuit which holds the output current of the rectifier practically constant during acceleration of the motor.

General Description of Inverter Action on Reversal

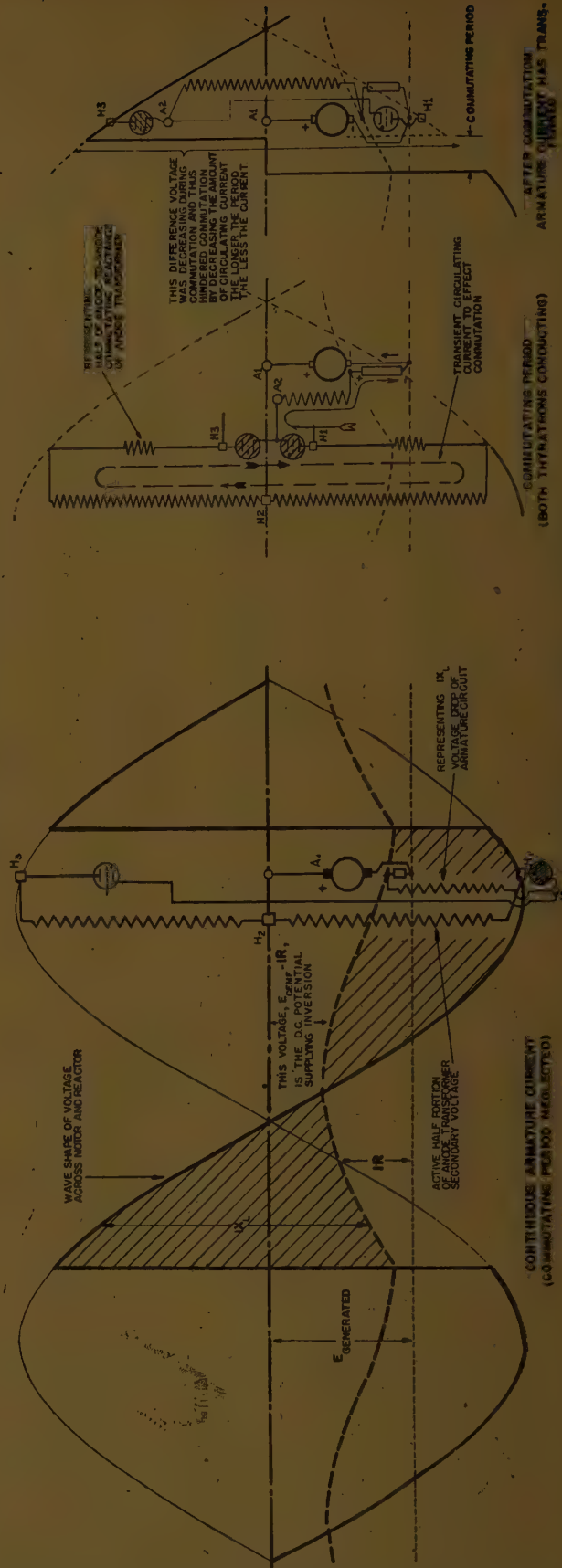
As was pointed out earlier, the case of a motor driven from a rectifier is not analogous to the normal operation of a generator driving a motor, because the current cannot reverse through the rectifier. A somewhat analogous operation of



Figure 2. Diagrammatic representation of d-c motor reversal with constant shunt field



RECTIFICATION - CONTINUOUS CURRENT



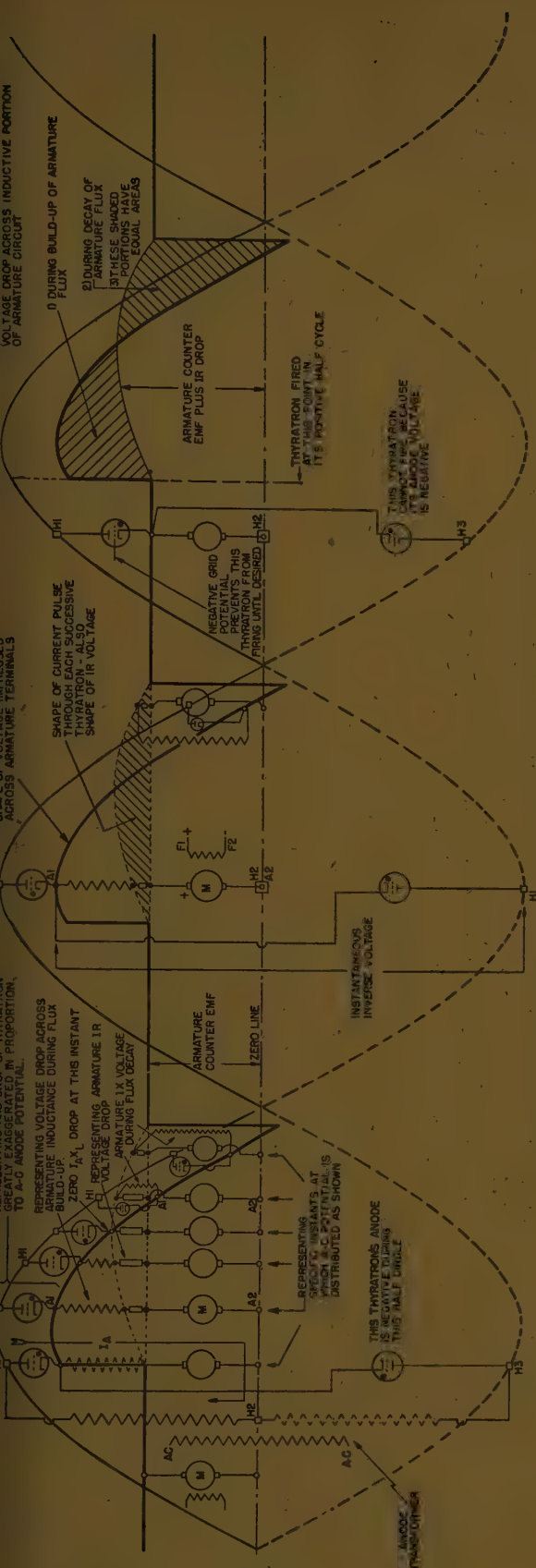
INVERSION - CONTINUOUS CURRENT

Figure 3. Graphic representation of continuous conduction rectification and inversion

a generator driving a motor can be drawn as pictured in diagrams A to D in Figure 2. A study of these figures will point out that, if the generator voltage is left unchanged, and the motor-armature connections are reversed, plugging and short-circuit current are the results; whereas,

if the polarity of the generator voltage is reversed before the reverse contactors to the motor armature are closed, and if the generator voltage is made lower than the generated voltage of the motor, regenerative braking results. The remainder of the diagrams, E to M,

in Figure 2 represent simple biphase grid controlled thyatron rectifiers supplying the armature of a d-c motor and operating under various stages of reversal. The motor field and all control is left out for simplicity. For the present the field excitation is assumed constant at i



RECTIFICATION (DISCONTINUOUS PULSES OF ARMATURE CURRENT)

Figure 4. Graphic representation of discontinuous conduction rectification and inversion

ductive until just before the transformer voltage connected to that anode goes negative. At the instant of firing, even though the transformer voltage is "near-ing-zero-going negative," the net voltage on the tube is considerably positive because of the generated voltage of the motor. As soon as the thyatron is made conductive, this net positive voltage is applied across the reactance and the resistance in the circuit.

The distribution of the various electromotive forces and voltage drops is pictured more clearly in Figure 3, for both rectification and inversion. In this graphic representation of the voltages the armature reactance and the series reactor drops are lumped together as one IX_L drop. Likewise, the armature and circuit resistances are lumped and greatly exaggerated in this diagram. The effect of tube drop is neglected.

The positive voltage across the reactance and resistance starts the current building up through the armature circuit. During the current build-up, energy is supplied to the reactance by the transformer voltage until this voltage reaches zero and by the generated voltage of the motor. As the transformer voltage drops from its initial value, the rate of current rise becomes less, until, when the transformer voltage becomes more negative than the difference between the generated voltage and the IR drop, the current begins to decay. During the decay of current and flux, all of the energy which was supplied to the reactance during the current build-up is returned to the transformer by an induced voltage which, added to the difference between the generated voltage and the IR drop, keeps the current flowing against the negative voltage of the transformer. The average voltage across the inverter then is the difference between the generated voltage and the average value of the IR drop, as indicated in Figure 2.

Stated differently, the average terminal voltage of the tube circuit is the average voltage of the transformer over the period in which the tubes are conducting current. If the tubes are fired early in the positive half cycle, the average transformer voltage during conduction is positive; so the average output voltage is positive. If the tubes are fired at the end of the positive half cycle with no other electromotive force in the circuit to cause current to flow, the average voltage output is zero. However, if there is another electromotive force in the circuit of the proper polarity to cause the tubes to conduct current against the opposing negative voltage of the trans-

former, the average terminal voltage of the tube circuit is negative.

Shifting the firing point changes the period of the a-c cycle over which the tubes are conducting and thus changes the average transformer voltage opposing or aiding the flow of current. When the average transformer voltage made effective by firing the thyatron is aiding the flow of current, the circuit is supplying power to the motor. When the transformer voltage is opposing the current flow caused by the generated voltage of the motor, the circuit is inverting power from the motor to the a-c system.

Retarding the firing point makes the average tube-circuit counter voltage more negative and, with a given generated voltage, decreases the average current. As the current is decreased with a given reactance in the circuit, the energy transfer in the reactance may be insufficient to maintain current over a full half cycle, so the current becomes discontinuous, as in Figures 4 and 5. If the tube firing can be retarded to the point where the transformer voltage becomes more negative than the generated voltage, there will be no current conduction.

Perhaps a better picture of the relation of continuous and discontinuous conduction is obtained by a consideration of the current and voltage components. The firing of the tubes controls the portion of the transformer voltage wave which is effective in the circuit. This voltage consists of an average component plus multiple-frequency ripple voltages, the chief of which is at twice line frequency for a biphasic circuit. The average current in the circuit is determined by the difference between the average effective transformer voltage and the generated voltage of the motor. The ripple current is determined by the reactance of the circuit. If the average value of current is greater than the negative peak of the ripple current, conduction is continuous. If the negative peak of the ripple current is greater than the average, the current becomes discontinuous, since the negative peak cannot reverse the current through the tubes. The transformer voltage then becomes ineffective until the next tube is fired. The value of the circuit reactance then determines the ratio of peak-to-average current and the conduction angle of the tubes.

With reference again to Figure 2, since the circuit is now taking energy from the motor instead of supplying it, the motor slows down, and the generated voltage drops. The grid voltage of the thyatrons is advanced to fire earlier in the cycle as

at H in order to keep the average negative voltage of the inverter less than the motor. As the firing point advances to an angle corresponding to the peak of the transformer voltage, the average tube-circuit terminal voltage becomes zero. Advancing beyond this point gives a positive average voltage, and the tube circuit, operating as a rectifier, supplies power to the motor.

The diagrams in Figure 2 demonstrate the fact that, to get current flow through the circuit, the average terminal voltage of the tube circuit must be less negative (or more positive) than the generated motor voltage. Then, to increase the current the firing point is advanced, and to decrease the current the firing point is retarded, both for inverter and rectifier operation.

Current Control

The current-limiting circuit of Figure 1, consisting of the current transformer, its rectifier, and tube E , measures the anode current and operates in the proper sense to control the firing point of the thyatrons during the inversion period as well as during rectifier operation. When the rectified voltage from the current transformer becomes equal to the 75 volts of the voltage-regulator tube E , tube E begins to function, unsaturating the reactor in the phase-shifting circuit and so phasing back the grid voltage of the thyatrons. Phasing back the firing point increases the average negative voltage which decreases the current until a balance is reached. This circuit then regulates the firing point during both inverter and rectifier operation to hold the current constant.

Preconditioning to Prevent Plugging

If the process initiating a reversal is so controlled that the forward contacts of the reversing switch are opened, but the reverse contacts not closed until after the grid voltage has been phase-retarded to the proper angle, the severe current peaks of plugging can be avoided. This operation will be referred to as preconditioning for a reversal.

During the interval when the reversing switch is completely open, with the motor armature disconnected from the circuit, the only load across the rectifier circuit is a high-resistance circuit. Because the resistor will not keep current flowing in the circuit after the anode transformer voltage goes negative, if the thyatrons are fired anywhere in the positive half cycle, the average output voltage is

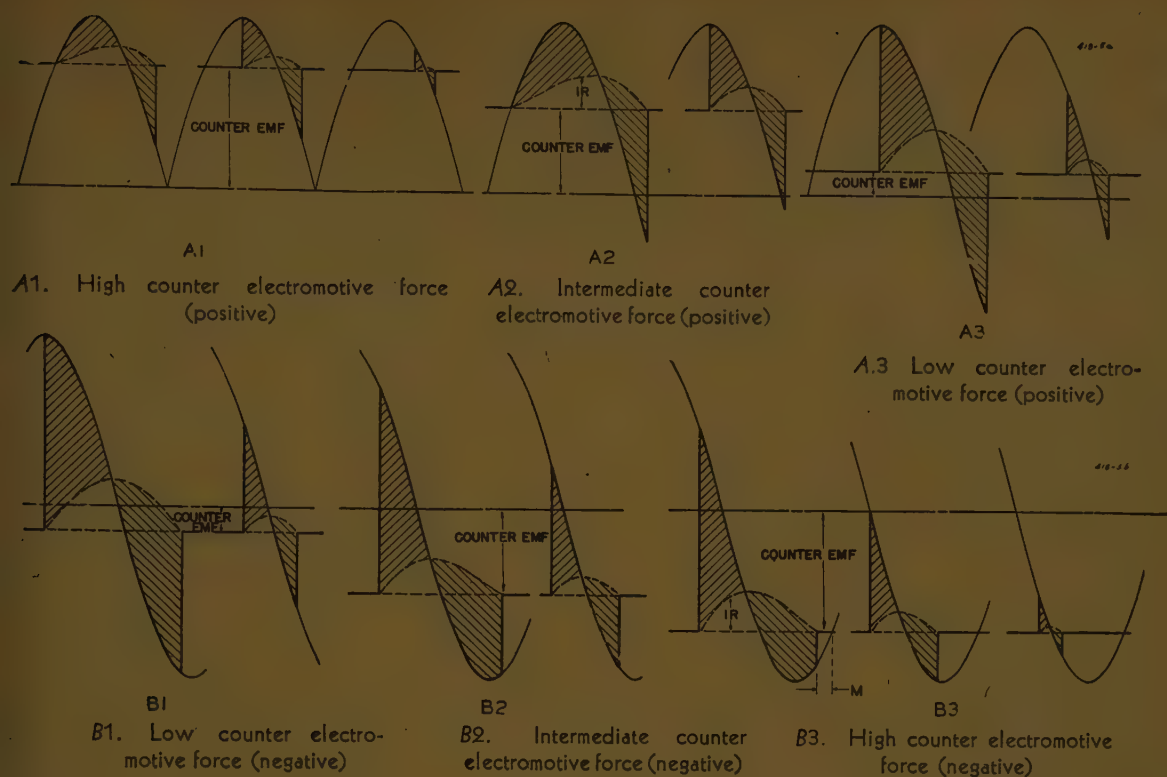


Figure 5. Effect of firing point and counter electromotive force on magnitude of anode current

A. Rectification—discontinuous currents

B. Inversion—discontinuous currents

M—Margin by which anode current does not become continuous and thereby tend to carry over into the region of rectification if not commutated out

positive and bears a definite relationship to the firing angle. Therefore, the positive voltage across the resistor load can be used as a measure of the firing angle. This relationship is utilized in the circuit of Figure 1 where the grid circuit of tube *E* is connected through a normally closed interlock, each on the forward and reverse contactors in series, to a tap on a resistance divider connected between a point 150 volts positive above neutral (point 5) and the positive side of the rectifier output (point 24). This serves to regulate the output voltage of the rectifier to a value which depends upon the ratio of the two sides of the resistance divider. By regulating to a low average voltage, the firing point of the thyatrons can be established at some point, such as in Figure 2G, which will give, upon closing the reverse contactor, the proper average negative voltage to limit the current to less than the current-limit value. A capacitor in the grid circuit of tube *E* "remembers" this conditioning signal momentarily, while the reverse contacts are closing, and the current is being established in the armature circuit. As this conditioning signal discharges from the grid capacitor the firing point is permitted to advance, increasing the current until the current signal takes over on tube *E*, which from there on limits the advance of the firing point to hold the current constant.

Where very fast forward and reverse contactors are used, it may be necessary to add a delay of a few cycles between the opening of the forward contacts and the

closing of the reverse contacts to permit the conditioning circuit to retard the grid-voltage phase. This is accomplished by using a small d-c relay operating on the time constant of a capacitor and resistor, as CR1 in Figure 1.

Commutation During Inversion

In Figure 3 is indicated graphically the process of commutation in the tube circuit, for both rectification and inversion. The commutation of the current from one tube to another depends on the instantaneous voltage and the commutating reactance of the anode transformer. The greater that voltage, the faster the current can build up in the incoming tube and go out in the offgoing tube through the commutating reactance of the transformer. Commutation can take place only on a tube of more positive-anode potential.

In the case of rectification, commutation is not difficult, because it is initiated in the period when the incoming anode is going positive, or the commutating voltage is increasing. In the case of inversion, commutation of the tube currents can become troublesome, because it is initiated in the period when the commutating voltage is decreasing. If it is initiated early enough in the cycle there is sufficient voltage to commutate the current, but if the firing is retarded to very near the end of the cycle where there is little voltage the "should-be-offgoing" tube's anode may start going more positive than the "should-be-incoming" an-

ode before commutation is complete. In that event the "should-be-offgoing" tube would take all the current again and conduct over the positive half cycle as well as the negative. This means that, while operating the biphas inverter at continuous current, the maximum retard of the firing point must be less than 180 degrees.

Maximum Voltage That Can Be Inverted

In a typical application of thyatron control to a 230-volt d-c motor, the maximum-armature speed-control setting is adjusted to give a speed corresponding to a counter electromotive force of 230 volts at full field. If then the anode transformer is designed to give an average output voltage of 280 volts, after allowing for tube drop, about 30 to 35 volts are left for *IR* compensation to hold the counter electromotive force and speed constant as the load is increased. If operated under this condition, the maximum-base-speed generated voltage that will be encountered will be 230 volts.

By comparison with rectifier operation it can be stated that, if the firing point could be retarded a full 180 degrees or to the zero voltage point and still effect commutation, with continuous conduction the negative voltage that could be developed would be equal in magnitude to the "full-on" rectifier voltage. A study of Figures 3 and 4 will show that tube drop subtracts from the rectifier voltage and adds to the negative inverter voltage

which can be developed. If the firing point is to be retarded slightly less than 180 degrees to insure commutation of the current from tube to tube, it is reasonable to expect a negative voltage slightly less in magnitude than the "full-on" rectifier voltage. The results of tests indicate that the maximum possible negative voltage for a biphas inverter is between 260 and 270 volts on the basis of 280 volts maximum average output as a rectifier.

Since the maximum-negative generated voltage that will be encountered will be 230 volts, with the motor running at base speed or below, the negative motor-terminal voltage developed during inversion will be less than this by the amount of the armature IR drop. Therefore, the firing point of the thyratrons normally will be well in advance of the zone which would involve commutation difficulties. Moreover, if the firing point is retarded to an angle which might produce trouble with commutation, the inverter voltage with continuous conduction would be more negative than the generated voltage. In that event, the current will be discontinuous, and it will not be necessary to commutate the current from tube to tube. This holds true only if the motor-terminal voltage is limited to about 230 volts which is the case for operation up to base speed of the motor.

Reversing From Field-Weakened Speeds

When the motor is to be operated at speeds above the base speed, the field is weakened by reducing the voltage of the field rectifier. The armature voltage is held the same as at base speed, 230 volts counter electromotive force plus the IR compensating volts. To fulfill the condition established previously, that the generated voltage does not exceed the base-speed voltage, the build-up of the field must be controlled during inversion. To obtain the maximum decelerating torque, however, the field should be strengthened at such a rate as to hold the generated voltage constant at the base-speed value.

The normal operation of the current signal on the field control is to strengthen the field at the limiting current. On attempting to invert at the same current limit, this control would raise the generated voltage beyond all control of the inverter. In the circuit of Figure 1 this voltage increase is prevented by tube HH and the heavy dotted circuit connected to it. The divider to which the

cathode of tube HH is connected is so proportioned that, if the average value of the voltage across the armature goes more than 200 volts negative, tube HH begins conducting and overpowers the current signal of tube EE to the grid of tube DD , thereby limiting the strengthening of the field. This regulates the reverse motor-terminal voltage to 200 volts until the motor decelerates to base speed. Thereafter, tube HH is cut off by its cathodes going positive, and the field is controlled by the regular current-limit circuit for the remainder of the reversal period.

Inversion With Only the Reactance of the Armature

In the foregoing analysis the rectifier-load circuit was assumed to be highly inductive, and in some places a series reactor was shown. The armature winding, the commutating field winding, and the series field winding, if used, have appreciable inductance. A typical one-horsepower 1,150-rpm 230-volt motor was found to have an inductance ranging from 0.15 henry to 0.05 henry, depending on the degree of saturation of the iron structure. This range of inductance at the 120-cycle ripple frequency of the biphas circuit is sufficient to give continuous conduction at weak field and 100 per cent current but discontinuous conduction at full field and the same current. Other motors operated from this type of thyatron rectifier operating at from 100 to 150 per cent rated current vary from near continuous to continuous conduction.

As was pointed out before, if the reactance of the circuit is fairly low, so that the peak ripple currents are high, or if the average direct current is limited to a very low value, the peak current may become greater than the average direct current

and so give discontinuous conduction, as in Figure 4; that is, the current goes out in one tube before it is initiated in the other. The voltage across the motor terminals has the general wave form indicated by the heavy line. It may be noted that, during the period when there is no conduction through the tubes, the only voltage evident at the output of the rectifier and the motor terminals is the generated or the counter electromotive force of the motor.

During rectifier operation the pulses of current may be quite short over the full range of voltage at light loads, lengthening out to nearly full, or full conduction at rated current, especially at weak field, if not at full field. The inverter operates normally between full load and 150 per cent full-load current, except for the first few cycles while the current-limiting-control circuit is advancing the firing point to give the current limit. Operating at the high direct current and with the inductance ordinarily encountered in fractional and small horsepower motors, the conduction angle of the tubes in a biphas system varies from about 135 degrees to a full 180 degrees. For the larger motors with less inductance, polyphase circuits, which have lower ripple voltages, are used; hence, the conduction angle is at or near $2\pi/P$ radians.

Although ordinarily operated at high current, the circuit will invert properly with the negative generated voltage at not more than 230 volts, at an average current well below the rated motor current, from one half to one fourth, by re-

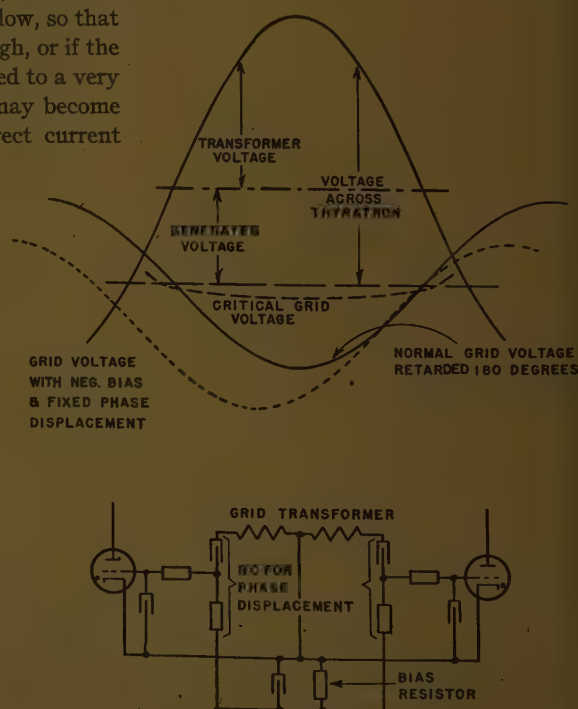


Figure 6. Alteration of grid voltage to permit firing late in the cycle

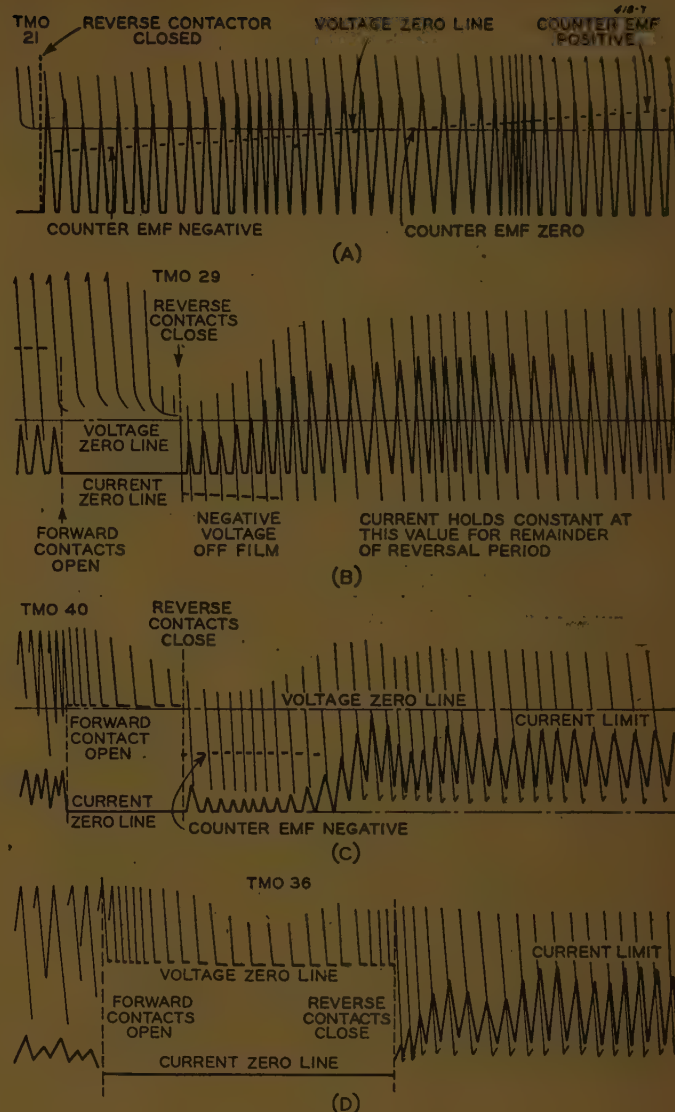
tarding the firing point to near 180 degrees. This means that on a reversal, if the pre-conditioning circuit retards the firing point to near 180 degrees while the contactors are open, the motor current upon closing the reverse contactor will be discontinuous current, as indicated in Figures 4 and 5, with an average value well below the rated value of the motor. After a cycle or two the current-limiting control will advance the firing point decreasing the opposing voltage of the inverter and increasing the average current to the limiting value. At this value it may still be slightly discontinuous or it may be continuous, as in Figure 3.

Discontinuous Operation With the Firing Retarded 180 Degrees

With discontinuous conduction there is not the commutation problem with late firing that is present with continuous conduction, since the current in one tube goes out before the other tube is fired. There is one precaution, however, that should be observed in connection with retarding the firing point a full 180 degrees. With the generated voltage of the motor reversed for inversion, the addition of the generated voltage and the transformer voltage gives a voltage across the thyatron which is positive for more than a half cycle, as shown in Figure 6. If the grid voltage is negative for only a half cycle, it cannot be retarded a full 180 degrees without causing the thyatron to fire just before or at the beginning of the positive half cycle instead of at the end of the positive half cycle as was intended. To fire at the beginning of the positive half cycle would give an extremely high peak current.

This condition can be avoided by one of two means. The retard of the grid voltage during the conditioning period while the armature contactors are open can be regulated to limit the angle to a safe position a few degrees less than 180. This will still hold the current upon closing the reverse contactor to less than the limiting value, and the firing point will advance as the current-limit control takes over. Misfiring may be prevented also by altering the grid-voltage wave, so that it is negative for more than 180 degrees. In Figure 6 is shown one possible method of altering the grid voltage to permit retarding the firing a full 180 degrees. This alteration was accomplished by adding to the sine-wave voltage from the grid transformer a negative bias and displacing the phase forward to bring the firing point to the same point as with the original grid voltage. The

Figure 7. Oscillograms of actual reversing operation of electronic drive



negative bias is a self bias by grid rectification. The phase displacement is by means of a resistor and capacitor. This grid circuit is included in the circuit of Figure 1.

With a grid voltage of this characteristic the circuit which conditions the tube for a reversal can be made to shift the firing point to a maximum retard without regulating. This could be accomplished in the circuit of Figure 1 by using the *F* and *R* contacts, which now connect the grid of tube *E* to a resistor divider, to connect the same grid to the cathode of tube *E*. This would serve as a false over-current signal to tube *E*, possibly giving a faster conditioning.

Oscillograms of Actual Reversing Operation

In Figure 7 are shown tracings of the voltage across the armature terminals and the armature current at the beginning of a reversal. The film was hand operated, so it is slightly irregular along

the time axis. Figure 7A does not include the opening of the forward contacts but does show one cycle of the preconditioned voltage. The preconditioning was adjusted to give a current at approximately the limiting value upon closing the reverse contactor. This oscillogram was taken with a one-horsepower motor with no connected load. The change of speed from full forward to near-full reverse can be followed by the trace of the generated voltage during the non-conducting period.

Figure 7B shows a full preconditioning period and the beginning of inversion. The firing was retarded by the preconditioning circuit to give a very low armature current upon closing the reverse contactor. This oscillogram was taken with a high inertia load on the motor, so that it slowed down very slightly in the time shown.

The oscillograms in Figures 7C and D were taken during a reversal from a field-weakened speed with a high-reactance motor. In Figure 7C, the current is dis-

continuous at the very low value on closing the reverse contacts but becomes continuous before the current limit is reached. Note that, while the current is discontinuous, the generated voltage shows up during the nonconducting period. In Figure 7D the current is continuous from the beginning.

Stopping the Motor by Regenerative Braking

Inversion can be utilized to bring the motor to a stop by regenerative braking. If, with the motor running at any speed, a normal reversal operation is started, and at the same time the reverse-direction speed control is switched to zero speed, the motor will decelerate by inversion, but at zero speed the voltage circuit will turn off the thyratrons. If then the switching devices are de-energized, a complete stop has been accomplished.

An example of a control circuit for this type of operation is included in the circuit of Figure 1. The relaying scheme is such that, when the stop button is operated, a reversal operation is started, reversing from whichever direction the motor was running when the stop button was pushed. This reversal is exactly the same as though it were initiated from either the forward or reverse push buttons, except that at the same time the reference voltage of the armature-voltage-control tube *C* is reduced to zero. It may be recalled from Figure 2 that during a normal reversal the voltage output of the rectifier at the instant of zero speed is not zero but is the *IR* drop of the motor. If the reference voltage of the armature-voltage-control tube is at zero, and if the *IR* compensating signal is still in operation, the rectifier will build up a positive voltage equal to the *IR* drop before the voltage-control tube takes hold. Since it requires no current to hold zero speed, the control quickly retards the firing point and, as the *IR* signal collapses, the rectifier voltage is reduced to zero. Turning the rectifier off de-energizes the *Z* relay, which in turn disconnects the other switching devices.

The deceleration is at constant horsepower during the field-control range of speed and at constant torque in the armature-control range right down to the last revolution.

Polyphase Circuits

Polyphase rectifier circuits may be made to invert in the same manner as

System Voltages and Fault Currents Determined Easily on D-C Board

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THE purpose of this paper is to outline a simple procedure that may be used to obtain short-circuit data most generally needed for relay co-ordination studies by using a d-c calculating table.

A fairly complete relay co-ordination study can be made on systems using overcurrent and directional overcurrent phase and ground relays based on the three-phase short-circuit current and the residual current for single-phase-to-ground faults. However, where ground relays have to be co-ordinated with phase relays, it is desirable to know also the value of current that flows through phase relays when ground faults occur.

Since the development of distance relays, it is also desirable to know the voltages at various locations in the transmission system during three-phase and phase-to-ground faults. Where the zero-sequence voltage is used to polarize ground relays, it would often be advantageous to know the value of zero-sequence voltage in the system at a number of points for ground faults at various locations. Where relays are applied using negative-sequence currents and voltages, it may also be desirable to know those values during ground faults. All of these currents and voltages can be calculated by the method of symmetrical components; however, the cal-

culations are quite lengthy and require considerable time. The same information can be obtained quickly and easily by the d-c calculating board and with relatively few and simple calculations. A description of the steps required is given in the next section. This is followed by a discussion of the factors involved and an analysis of the method.

Description of Method

1. Set up the positive-sequence network on a convenient kilovolt-ampere base using reactances and impedances to give the desired accuracy.
2. Set up the zero-sequence reactances on one half the kilovolt-ampere base used for the positive-sequence network.
3. Take current readings for a three-phase fault at any point in the positive-sequence network. If possible use 100 volts on the board at all times. If it is not possible to use 100 volts, use whatever voltage that is convenient to represent 100 per cent voltage.
4. With a three-phase fault applied, read and record voltages on various busses of interest over the system by using a high-resistance voltmeter. The voltage measured from the three-phase fault to a particular bus in the positive-sequence network divided by the total board voltage and multiplied by 100 gives the per cent voltage on that bus. If the total board voltage is 100 volts, the voltmeter reading represents per cent voltage at the point being considered. Record this as *V*.
5. Apply a fault at a point in the zero-sequence network corresponding to that used for the three-phase fault in item 3, using the same voltage that was used for the three-phase fault. Read the total fault current and the distribution in the zero-

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the biphasic circuit and with practically the same control circuit. There is one restriction for polyphase inversion that is not present for rectification. The grid voltage of the thyratrons for inversion must remain positive for an angle of not more than $2\pi/P$ radians where *P* is the number of phases.

In three- and four-phase circuits the inversion current can be limited to rated motor current or less by retarding the firing point a full 180 degrees. In six-phase circuits the firing point must be

retarded more than 180 degrees beyond the beginning of the positive half cycle to limit the current properly.

In polyphase circuits, commutation at 180 degrees firing is not difficult with continuous current, since the voltages of adjacent phase do not go to zero at the same time.

Reference

1. THYRATRON MOTOR CONTROL, E. E. Moyer, H. L. Palmer. AIEE TRANSACTIONS, volume 62, 1943, November section, pages 706-12.

sequence network on a scale having 3/2 as many divisions as the scale used for three-phase faults. These currents represent residual currents in the system and are the currents that will flow through ground relays for a phase-to-ground fault. If the 3/2 scale is not available, use the same scale that was used to read three-phase faults and multiply the results by 3/2 to give residual amperes.

6. While the phase-to-ground short circuit is still applied, use a high-resistance voltmeter and measure the voltage from the neutral bus (zero potential plane) in the zero-sequence network to the various busses of interest in the zero-sequence network. If a total board voltage of 100 volts is being used, the voltage read is the per cent zero-sequence voltage at the bus where the voltage is measured. If 100 volts is not used for the total board voltage, the reading divided by the total board voltage times 100 will give the per cent zero-sequence voltage. Record the voltage measured as V_0 , a positive quantity.

7. With the phase-to-ground fault still applied, measure the voltage from the fault to the corresponding busses, in the positive-phase-sequence network, that were used to determine V_0 . Record the voltage measured as V_{12} . The voltage V_{12} is the positive plus the negative-sequence voltage at the point where the voltage is measured in the positive-phase-sequence network. The reading will be in per cent if 100 volts is being used for a total board voltage. Otherwise, the reading over the total board voltage times 100 will give the per cent voltage.

8. The current which flows in the phase relays of the faulted phase during a ground fault may be calculated easily from data already taken by using the following relationship.*

$$I_{\phi 1} = \frac{I_G}{3} \left(2 \frac{R_{P1}}{R_P} + \frac{R_{G1}}{R_G} \right)$$

9. The voltage at any point during a line-to-ground fault may be obtained from the following relationships. (Assume line A to be the faulted line.) The line-to-ground voltage expressed in per cent will be

$$\begin{aligned} E_A &= V_{12} - V_0 \\ E_B &= -V_0 - 0.5V_{12} - j86.6 \\ E_C &= -V_0 - 0.5V_{12} + j86.6 \end{aligned}$$

where V_0 and V_{12} are expressed in per cent.

The line-to-line voltage expressed in per cent will be:

$$\begin{aligned} E_{AB} &= E_B - E_A & E_{CA} &= E_A - E_C \\ E_{BC} &= E_C - E_B \end{aligned}$$

where all voltages are taken vectorially. Care must be taken where transformations are involved to consider the phase-angle displacement of each of the component voltages before combining them vectorially.

10. The positive- or negative-sequence component of voltage at any point during a ground fault may be obtained from the voltage readings already recorded as

$$V_2 = \frac{E_G - V_{12}}{2}$$

* See definition of symbols at the end of the paper.

If

$$E_G = 100$$

then

$$V_2 = \frac{100 - V_{12}}{2}$$

$$V_1 = V_{12} + V_2$$

where V_{12} and V_2 are both considered as positive quantities. The sequence components of currents in any branch of the circuit during a ground fault may be obtained from the following relationships:

$$I_1 = I_2 = \frac{I_G}{3} \times \frac{R_{P1}}{R_P} \quad I_0 = \frac{I_G}{3} \times \frac{R_{G1}}{R_G}$$

(I_2 and V_2 may be of interest where negative-sequence ground relays are being applied.)

Using Reactance or Impedance

When voltages are to be determined for use in determining distance relay performance, consideration should be given to whether reactance or impedance values are to be used in setting up the networks. If the ratio of reactance to resistance is fairly high, the result obtained will be sufficiently accurate if reactance is used. If the resistance is an appreciable part of the total impedance, a more accurate result may be obtained by using impedance rather than reactance. The particular system under consideration should be studied and the various constants compared to decide wisely on whether impedance or reactance should be used. It may be that in part of the network reactance values should be used and in other parts impedance values would give better results.

In the zero-sequence network it will be found usually that the ratio of X/R is high enough that reactance only may be used throughout with little error. However, for a high-resistance grounded system this, of course, would not be the case.

Choosing a Base

After the proper constants have been determined for the positive- and zero-sequence networks, a base should be chosen so as to utilize the rheostats available without having to put too many in series for a given line section nor too many in parallel for other lines, transformers, or generators. Due consideration also must be given to the range of the galvanometer readings and accuracy to which resistor settings can be made. It should be kept in mind that low-scale deflections on the galvanometer have not only a sizeable per cent error due to the observation but also an appreciable error

due to the accuracy of the galvanometer, which has a guaranteed accuracy in a certain per cent of full scale.

Networks Needed

It is desirable to set up as few networks as possible and still obtain the desired information. Since the positive- and negative-sequence networks are very similar, little error results in most short-circuit studies by considering the two networks to be identical and setting them up as one network. The zero-sequence network is also necessary for ground-fault studies. Set up the positive-sequence network on the desired base and set up the zero-sequence network on a base one-half the size of that used for the positive-

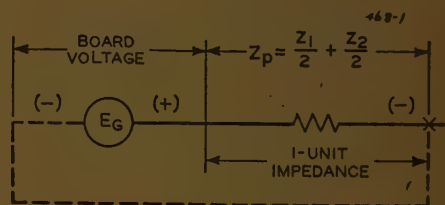


Figure 1. Three-phase fault with unit voltage and unit impedance

Unit current or base kilovolt-amperes flow to the fault

sequence network. These two networks are all that is required to give quite a complete study of currents and voltages for three-phase and phase-to-ground faults.

Three-Phase Faults

Consider the two networks in their most simple form as shown in Figures 1 and 2 on a per unit base. For clarification consider

$$Z_1 = Z_2 = Z_0 = \text{unit impedance}$$

Let

$$Z_{1/2} + Z_{2/2} = Z_P$$

For a three-phase fault, if one unit of voltage is impressed on one unit of impedance, one unit of current flows, which means that base kilovolt-ampere is flowing to the fault. Therefore, the network in Figure 1 may be used to determine three-phase faults.

Phase-to-Ground Fault

Consider a simple system having unit positive-, negative-, and zero-sequence impedances. Such a system has unit three-phase fault current and unit ground-fault current. If the zero-sequence impedance is set up on one-half the base

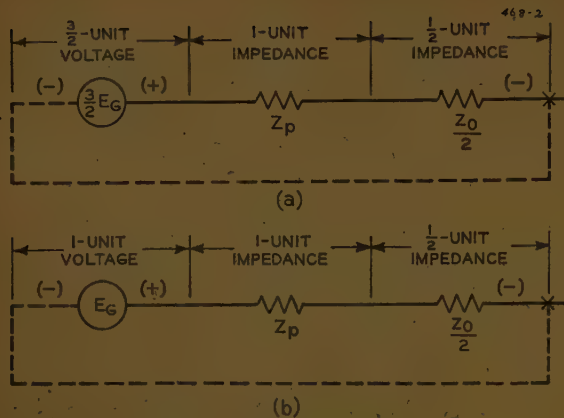


Figure 2. Phase-to-ground fault

used for the positive-sequence network, as shown in Figure 2, then there exists 3/2 units of impedance to the fault. If 3/2 units of voltage were impressed on the network as shown in Figure 2a, unit current or base kilovolt-amperes would flow to the fault, this being the correct ground-fault current. However, it is usually more convenient to use the same board voltage for three-phase and phase-to-ground faults, and then for ground faults multiply the current readings by 3/2 or use a second scale on the galvanometer calibrated to read 50 per cent higher than the first. This second scale then reads the correct residual current, that is, the current which flows through ground relays operating on residual currents. The distribution of currents read in the zero-sequence network is the true distribution of residual current in the various branches of the network under consideration. This is apparent from the following consideration of Figures 3a and 3b.

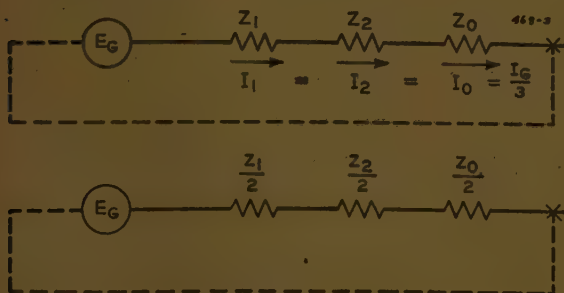
In each figure consider $Z_1 = Z_2 = Z_0 = Z$ for simplification.

In Figure 3a, if unit voltage is impressed on 3 units of impedance 1/3 unit current flows. This in the ordinary consideration of symmetrical components is called

$$I_1 = I_2 = I_0 = I_g/3$$

where I_g is the residual current.

$$\frac{I_g}{3} = \frac{E_g}{Z_1 + Z_2 + Z_0} = \frac{E_g}{3Z}$$



(a). (3/2) unit voltage applied

$$I = \frac{(3/2)E_g}{(3/2)Z} = \frac{E_g}{Z}$$

Therefore, unit current or base kilovolt-amperes flow to the fault

(b). One-unit voltage applied

$$I = \frac{E_g}{(3/2)Z} = \frac{2}{3} \frac{E_g}{Z}$$

Therefore, two thirds of unit current or of base kilovolt-amperes flows to the fault

or

$$I_g = \frac{3E_g}{3Z} = \frac{E_g}{Z} = \text{unit current} \quad (1)$$

Figure 3b is the same fundamentally as that shown in Figure 2b, and if unit voltage is impressed on 3/2 units of impedance, 2/3 units of current flows, that is

$$\frac{E_g}{\frac{Z_1}{2} + \frac{Z_2}{2} + \frac{Z_0}{2}} = \frac{E_g}{(3/2)Z} = (2/3) \frac{E_g}{Z} \quad (2)$$

If a multiplier of 3/2 is used or a 3/2 scale used as described previously then

$$(3/2) \times (2/3) \frac{E_g}{Z} = \frac{E_g}{Z} = I_g, \text{ the residual current}$$

Therefore, the current determined by using the 3/2 multiplier or as read on the 3/2 scale in the networks shown in Figure 2b or 3b is residual current.

Voltage During Three-Phase Faults

The voltage at any point in a network during a fault is the vector sum of the voltages at that point in each of the sequence networks. The voltage at any point for a three-phase fault is the generated voltage minus the IZ drop to the point being considered, or the IZ drop from the fault to the point under consideration. Since no zero- or negative-sequence currents flow during a three-phase fault, only the positive-sequence network need be considered

for voltage at any point. If the voltage is measured from the fault to the point where the voltage is desired in the positive-sequence network, when a three-phase fault is applied; the value obtained is proportional to the line-to-neutral voltage at that location. The measured voltage divided by the d-c board voltage times 100 is the per cent of the system voltage that exists at the point under consideration. If the d-c board voltage is 100, the voltmeter reads per cent voltage. This is shown in Figure 4.

Voltages During a Phase-to-Ground Fault

When a phase-to-ground fault occurs on a grounded system, positive-, negative-, and zero-sequence currents flow, and the voltage at any point is the vector sum of the positive-, negative-, and zero-sequence voltages at that point. Each of the sequence voltages is produced by its particular sequence current flowing

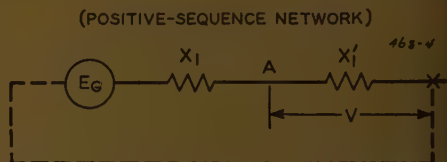


Figure 4. Voltage during a three-phase fault

The per cent voltage at point A is $(V/E_g)100$. If $E_g = 100$ volts, then V is the per cent voltage at A

through that sequence impedance. The voltage in each network at a given point is the generated voltage in that network minus the IZ drop to the point being considered. Since the positive-sequence network is the only one having a generated voltage, the expressions for the sequence voltages at a given point, L , are

$${}_L E_1 = E_g - I_1 Z_1 \quad (3)$$

$${}_L E_2 = 0 - I_2 Z_2 \quad (4)$$

$${}_L E_0 = 0 - I_0 Z_0 \quad (5)$$

The phase-to-neutral voltage on the faulted phase, say A, at the point L is

$${}_L E_A = {}_L E_0 + {}_L E_1 + {}_L E_2$$

From symmetrical components the voltages to neutral on the two unfaulted phases are

$${}_L E_B = {}_L E - 0.5({}_L E_1 + {}_L E_2) - j0.866({}_L E_1 - {}_L E_2)$$

$${}_L E_C = {}_L E - 0.5({}_L E_1 + {}_L E_2) + j0.866({}_L E_1 - {}_L E_2)$$

As indicated by equations 3, 4, and 5, ${}_L E_1$ is positive and ${}_L E_2$ and ${}_L E_0$ are negative for the phase-to-ground fault condition

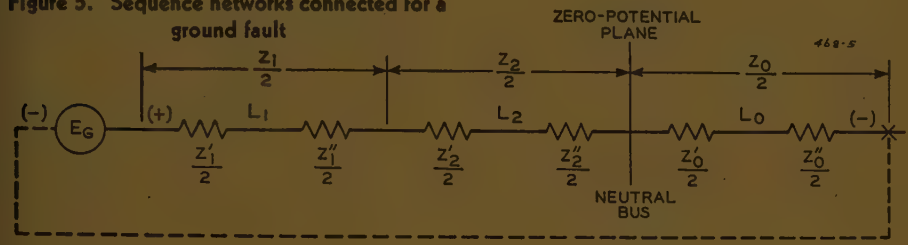
Figure 3. Residual current read directly for phase-to-ground faults

(a—above). Network with actual impedances
(b—below). Network with impedances as set on calculating table

in which I_2 and I_0 are in the same direction as I_1 . In the following material, therefore, the E 's are used to include the significance or relative direction, whereas V 's are all positive numbers and must be used with appropriate signs. Thus ${}_LE_1 = {}_LV_1$, and these are used interchangeably. However, ${}_LE_2 = -{}_LV_2$, and ${}_LE_0 = -{}_LV_0$. The E 's are actually vectors, although those obtained directly from the d-c board are all in phase or 180 degrees out of phase. Thus, it is consistent later to use the symbol E in expressions for vectorial voltages of the other phases.

It is often desirable to know the voltages at several locations during a phase-to-

Figure 5. Sequence networks connected for a ground fault



ground fault to predict the performance of voltage relays, distance relays, under-voltage devices, or the general system disturbance. It is also often desirable to know the zero-sequence voltage at a number of locations to determine the performance of directional ground relays using zero-sequence voltage for polarization.

ZERO-SEQUENCE VOLTAGE

From equation 5 above the zero-sequence voltage at the point L is the $I_0 Z_0$ drop from the zero potential plane or neutral bus of the zero-sequence network to the point L . The current flowing in the zero-sequence network as set up in Figure 2b is $(2/3)I_G = 2I_0$. The impedance used in this network, however, is set up on one-half the normal base used for the positive-sequence network, and the value of zero-sequence impedance in the network on a per unit base is $Z_0/2$. If two times unit current flows through one-half unit impedance, unit voltage is produced or $2I_0 Z_0/2 = I_0 Z_0 = {}_LV_0$. Therefore, the voltage measured from the zero potential plane or neutral bus to point L in the zero-sequence network represents the zero-sequence voltage at the point L . If E_G is 100 volts, then $({}_LV_0/100) 100 = {}_LV_0$. Therefore, if $E_G = 100$, ${}_LV_0$ is the per cent zero-sequence voltage at point L . The per cent zero-sequence voltage, ${}_LV_0$, is the per cent of the maximum zero-sequence voltage which is the same

as three times the normal line-to-neutral voltage.

GROUND-RELAY VOLTAGE

If the secondary or relay zero-sequence voltage corresponding to 100 per cent primary zero-sequence voltage is known, the per cent zero-sequence voltage, ${}_LV_0$ divided by 100 and multiplied by this secondary voltage will give the zero-sequence volts on the ground relay. The most common method of obtaining polarizing voltage for ground relays is to use wye-wye main potential transformers, grounded on each side, and wye-broken-delta auxiliary potential transformers with the wye grounded. With this com-

bination the polarizing voltage on the relay can be obtained readily for the condition of 33 per cent zero-sequence voltage. This condition is simulated when the primary of one main potential transformer is disconnected from the line and short circuited with the other two transformers energized from the two remaining lines of the three-phase source.

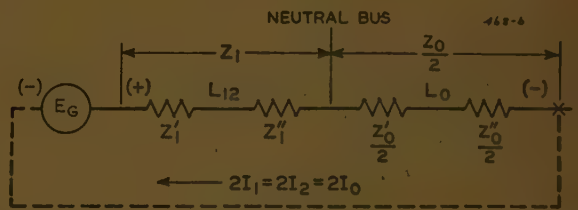
For example, suppose the phase-to-neutral voltage is 19,000 volts, and potential is supplied to the ground relay through three 300/1 ratio wye-wye main potential transformers connected to three 1/1.73 ratio wye-broken-delta auxiliary transformers. The relay voltage for the simulated 33 per cent zero-sequence voltage condition is then

$$(19,000/300)1.73 = 110 \text{ volts}$$

or 100 per cent zero-sequence voltage corresponds to 330 volts on the relay.

It may be found helpful to record this 100 per cent secondary zero-sequence voltage on the reactance diagram at all the points where the zero-sequence voltage is of interest for future reference, thus eliminating duplicate calculations.

Figure 6. Sequence networks connected for a ground fault with positive- and negative-sequence networks combined



Since various ratio auxiliary potential transformers are used often at different locations, the advantage of recording the maximum secondary zero-sequence voltage is apparent. $(V_0/100) 330$ is the voltage on the ground relay in the aforementioned example. V_0 seldom exceeds 60 per cent for a solidly grounded system and is more often 33 per cent or less.

POSITIVE- AND NEGATIVE-SEQUENCE VOLTAGES

It will be shown first that the sum of positive- and negative-sequence voltages can be read directly from the calculating board. Figure 5 is an equivalent diagram of the network arrangement on the board with the point L identified in each network. Let E_G be unit voltage, and $Z_1 = Z_2 = Z_0 = 1$ unit of impedance.

Since unit voltage is impressed on a total of $3/2$ units of impedance, $2/3$ units of current flow, as was shown in Figure 2b. Since unit current is I_G , the current that flows is $2/3 I_G = 2I_0 = 2I_1 = 2I_2$.

The positive- and negative-sequence impedances being identical may be combined as shown in Figure 6, the current being the same as in Figure 5. The positive- and negative-sequence voltages during a ground fault at point L of Figure 6 are shown in Figure 7. They are derived as follows from Figures 5 and 6:

$${}_LE_1 = E_G - \frac{2I_1 Z_1'}{2}$$

$${}_LE_2 = 0 - \frac{2I_2 Z_1'}{2}$$

$${}_LE_1 + {}_LE_2 = E_G - \frac{2I_1 Z_1'}{2} - \frac{2I_2 Z_1'}{2} = E_G - 2I_1 Z_1'$$

Let

$$E_G - 2I_1 Z_1' = {}_LV_{12}$$

$${}_LV_{12} = {}_LE_1 + {}_LE_2$$

Note that ${}_LV_{12}$ is the voltage that exists between the fault on the board setup and the point L in the positive-sequence network when a ground fault exists. If E_G is 100, ${}_LV_{12}$ is in per cent.

From equation 4 the negative-sequence voltage at point L is

$${}_LE_2 = -I_2 Z_2'$$

Since Z_2' is assumed equal to Z_1' and $I_2 = I_1$, and if it is noted from Figure 7 that

$I_1 Z_1' = (E_G - L V_{12})/2$, therefore

$$L E_2 = -I_1 Z_1' = -(E_G - L V_{12})/2$$

or the numerical value of negative-sequence voltage is

$$L V_2 = (E_G - L V_{12})/2$$

It is in per cent if $E_G = 100$.

The positive-sequence voltage at point L is

$$L E_1 = L V_{12} - L E_2$$

since $L V_{12}$ is equal to $L E_1 + L E_2$. However, E_2 is negative and has the magnitude $L V_2$. Thus

$$L V_1 = L E_1 = L V_{12} + L V_2$$

PHASE-TO-GROUND VOLTAGES

The expressions for line-to-ground voltages in terms of board measurements may be derived as follows. The per cent

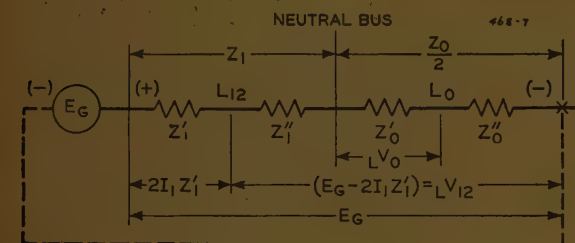


Figure 7. Voltage measurements for a ground fault

phase-to-ground voltage on the faulted phase, say A , at point L is

$$E_A = L E_1 + L E_2 + L E_0 = L V_{12} - L V \quad (\text{since } L E_0 \text{ is negative})$$

From symmetrical components

$$L E_B = L E_0 - 0.5(L E_1 + L E_2) - J0.866(L E_1 - L E_2)$$

$$L E_C = L E_0 - 0.5(L E_1 + L E_2) + J0.866(L E_1 - L E_2)$$

$$(L E_1 + L E_2) = V_{12}$$

$$L E_1 - L E_2 = (E_G - I_1 Z_1') - (0 - I_2 Z_2')$$

$$L E_1 - L E_2 = E_G$$

$$L E_B = -L V_0 - 0.5 V_{12} - J0.866 E_G$$

$$L E_C = -L V_0 - 0.5 V_{12} + J0.866 E_G$$

As stated previously, $L V_0$ and V_{12} both are considered as positive numbers. If $E_G = 100$, the phase-to-ground voltages at point L become

$$L E_A = V_{12} - L V_0$$

$$L E_B = -L V_0 - 0.5 V_{12} - J86.6$$

$$L E_C = -L V_0 - 0.5 V_{12} + J86.6$$

All values will be in per cent of phase-to-neutral voltage at point L .

LINE-TO-LINE VOLTAGES

The line-to-line voltages in per cent of line-to-neutral voltage will be

$$L E_{AB} = L E_B - L E_A \text{ taken vectorially}$$

$$L E_{BC} = L E_C - L E_B \text{ taken vectorially}$$

$$L E_{CA} = L E_A - L E_C \text{ taken vectorially}$$

Conclusion

A complete picture of currents and voltages may be determined with sufficient accuracy for most relaying problems in a system during short circuits by using a d-c calculating board with very little more time and effort than is normally used to measure currents for three-phase and phase-to-ground faults. Only one setup, using two simple networks, is required. The only readings necessary are current or kilovolt-ampere for three-phase and line-to-ground faults, including

$I_{\phi 1}$ = current flowing through phase relays in branch 1 for a ground fault

I_1 = positive-sequence component of current

I_2 = negative-sequence component of current

I_0 = zero-sequence component of current

Z_1 = positive-sequence impedance

Z_2 = negative-sequence impedance

Z_0 = zero-sequence impedance

R_P = reading for total three-phase fault

R_{P1} = reading for branch 1 for a three-phase fault

R_G = reading for total ground fault

R_{G1} = reading in branch 1 for a ground fault

(Note that kilovolt-amperes or amperes may be substituted for R_P , R_{P1} , R_G , R_{G1} if more convenient.)

E_G = unit voltage or 100 per cent voltage on the d-c board

V = voltage measured from the fault to some point where the voltage is desired in the positive-sequence network when a three-phase fault is applied

V_{12} = voltage measured on the board from the fault to some point where the voltage is desired in the positive-sequence network when a phase-to-ground fault is applied

V_0 = voltage measured on the board from the neutral bus or zero-potential plane to some point where the zero-sequence voltage is desired in the zero-sequence network when a phase-to-ground fault is applied

$L V_0$ = voltage that exists on the board from the neutral bus to a point of interest in the zero-sequence network designated as L

the current distribution of each desired, and V , V_{12} , V_0 , for each fault condition at as many points as the voltage may be of interest.

Other values of voltages and current such as V_1 , V_2 , V_A , V_B , V_C , I_1 , I_2 , I_0 , I_{ϕ} may be obtained by very simple calculations by using the currents and voltages that were measured. The voltage calculations are simplified by using a total board voltage of 100 volts, so that the voltmeter reads directly in per cent. The same result may be obtained where a board voltage other than 100 must be used by preparing a special scale for the high-resistance voltmeter which is marked in per cent of full board voltage, or by converting the readings taken into per cent of full board voltage.

Thus, a complete analysis of performance for modern relays may be made quickly and with sufficient accuracy for both three-phase and phase-to-ground faults by using the d-c calculating board and a high-resistance voltmeter.

Definitions of Symbols Used

I_G = total residual amperes flowing to a ground fault

(Note that the subletter L is also used to designate various other voltages which exist at point L .)

E_1 = positive-sequence component of voltage

E_2 = negative-sequence component of voltage

E_0 = zero-sequence component of voltage

E_A = the line-to-ground voltage on phase A

E_B = the line-to-ground voltage on phase B

E_C = the line-to-ground voltage on phase C

V with subscript designates absolute magnitude of the vector E with same subscript, namely, V_2 is magnitude of E_2 .

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Corona in Aircraft Electric Systems as a Function of Altitude

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Synopsis: Corona-starting voltages of the components of a 208-volt 400-cycle grounded-neutral electric system are reported for conditions to simulate altitudes between sea level and 50,000 feet. The corona characteristics are shown to be functions of air pressure, electric-field geometry, humidity, and the cleanliness of insulating surfaces. The effect of reducing pressure is shown to lower the corona-starting voltages of aircraft cables by as much as 60 per cent because the dielectric strength of large air gaps drops a comparable amount. Reducing the pressure has small effect on the corona-starting voltages of low-voltage capacitors, because the dielectric strength of small air gaps is nearly independent of pressure. Moisture and dust on insulating surfaces and moisture in aircraft cables produce corona-like disturbances below 208 volts. Data are presented on cables, capacitors, parallel studs, and needle gaps. Under dry conditions all corona-starting voltages were well above the operating voltages of the system.

CORONA in an electric system consists of minute arcs which produce ozone and nitrous acid in air; they carbonize oil, paper, and cotton; they oxidize and age rubber, and they corrode metal. Corona at operating voltages has often caused the rapid deterioration of the electric equipment containing the corona. In addition, high-frequency radiation is produced which may interfere with radio and allied instruments. For these reasons engineers working in the design and development of electric equipment should know the voltage at which corona first appears in that equipment.

Corona in insulation usually consists of the breakdown of small air pockets and gaps. It is well known that at high altitudes the density and dielectric strength of air are reduced greatly from their sea-level values. The change from sea level to 50,000 feet causes the dielectric strength of a one-centimeter parallel-plane air gap to drop by more than 75 per cent. Because of this, the

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question has been raised as to whether corona-starting voltages would not also drop greatly at high altitudes. This paper is an attempt to answer that question in a manner to be helpful in general design. Emphasis is placed on the specific problem of determining

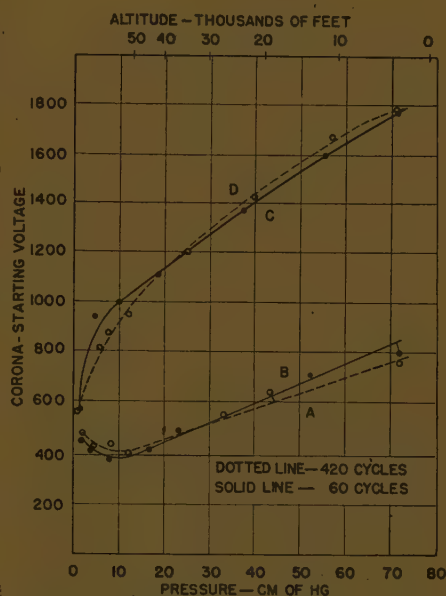


Figure 1. Effect of frequency upon the corona-starting voltage of cables

Curve A—Cable 1 at 420 cycles
Curve B—Cable 1 at 60 cycles
Curve C—Cable 4 at 60 cycles
Curve D—Cable 4 at 420 cycles

whether or not corona will exist in the steady-state operation of a 208-volt 400-cycle electric system.

Corona measurements were made upon the following:

Aircraft cables..... Figures 1, 2, 3, and 4
Table II
Capacitors..... Figure 5, Table I
Meter-case back..... Figures 6 and 7
Parallel studs..... Figures 8 and 9
Needle gaps..... Figure 10
Contaminated surfaces..... Table III

Variables were pressure, humidity, voltage, and frequency.

At the close of the report, data are discussed which deal with the increase of the sparking potential of small gaps as the gap is made smaller. It is shown

that this variation has great influence on the corona-starting voltage of capacitors at altitudes easily attained today.

All tests were made at room temperature and at an altitude of 1,000 feet. A method is given for correcting accurately the data on corona and breakdown in air to the low temperatures of high altitudes.

Method of Test

When corona occurs in any piece of equipment to which voltage is applied, the current to that piece of equipment includes high-frequency components. In many cases the high-frequency components can be separated from the normal charging currents, be amplified, and be viewed on the screen of a cathode-ray oscilloscope. With sufficient sensitivity at his control, an operator can thus detect the first pulses of corona and find the lowest voltage at which deterioration due to this cause can exist. A simple method for accomplishing these measurements has been described by G. E. Quinn.²

It is characteristic of this type of measurement that corona in a low-capacitance system, such as a needle gap, is much easier to detect than corona in a high-capacitance system. In the tests to be described in this report, the sensitivity was such that the first indication of corona was usually an off-scale deflection of the oscilloscope spot. The equipment was designed for more difficult high-capacitance work, and the results of that work check years of insulation experience. Because all of the tests in this paper were on low-capacitance samples, the writer feels that if there was any minute amount of undetected corona in the electric fields studied, it was negligible.

The tests were made with the samples in a desiccator which could be evacuated to two millimeters of mercury. Two diametrically opposite electric connections were brought into the desiccator and, when necessary, terminated in spheres. This insured that there would be no corona except in the test sample.

All tests were run at room temperature and, except when stated otherwise, with a drying agent in the desiccator. All tests were run at 60 cycles except those which were made to show that the frequency change from 400 to 60 cycles had small effect. When not stated otherwise, voltages are rms.

In this paper, corona is defined as ionization in a fluid dielectric without the breakdown of the sample in which the fluid is contained. Examples are numer-

ous. Ionization may occur in air around metal points or in oil between transformer windings. If the test piece does not become a conductor from terminal to terminal, the ionization is defined as being corona. In air, oil, and other good dielectrics corona appears in a characteristic manner. The fluid suddenly ionizes at a certain voltage; at that voltage a large deflection of the oscilloscope spot can be seen.

In the tests involving moist samples the pulses detected were of a different type. The pulses, instead of first appear-

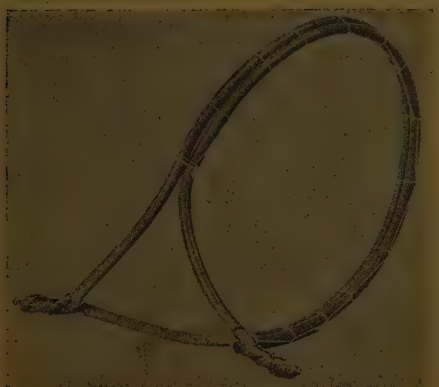


Figure 2. Form of cable-to-cable samples

ing with a large deflection, often grew from an indetectable first amplitude. This type of disturbance was also called corona because the moisture which caused the disturbance was part of the dielectric. It could not always be differentiated from ionization in air. The only tests which gave indications of ionization at voltages near 208 volts were tests with very moist samples.

The corona-starting and the breakdown curves are plotted against the pressures at which the tests were run. A second scale gives the altitudes which correspond to the test conditions insofar as corona or breakdown in air are concerned. As explained later in the paper the tests made at room temperature and at variable pressure have been corrected to high-altitude temperatures and pressures. The equivalent altitudes apply accurately when the ionization occurs in air, but they do not apply when the ionization occurs in a liquid such as in the moist cables. In the latter tests the equivalent conditions are doubly uncertain because the water will freeze at high altitudes unless the equipment is heated.

Frequency—Figure 1, Table I

The influence of frequency on corona in air which includes no solid barriers

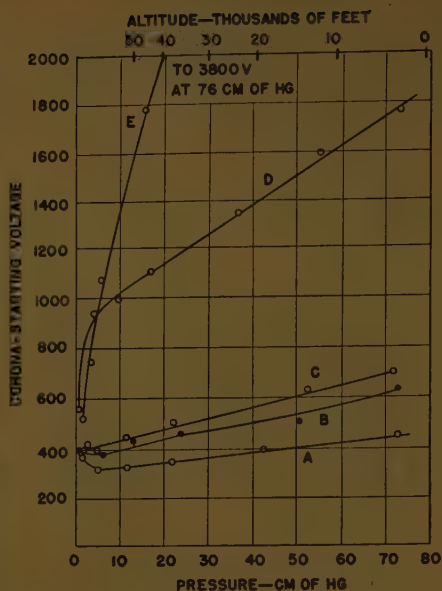


Figure 3. Corona-starting voltages of cables at room humidity

- Curve A—Number 8 cable to cable
- Curve B—Number 1/0 cable to cable
- Curve C—Number 16 cable to cable
- Curve D—Cable 4
- Curve E—Cable 5

has been shown by Peek³ to be negligible through the frequency range from 60 to 420 cycles. Data taken for this paper show that the corona-starting voltages of fields with solid barriers are not affected by more than ten per cent by the aforementioned change in frequency.

For example, Figure 1 shows the corona-starting voltages of two cables tested at varying pressure and at both 60 and 420 cycles. There is no significant difference between the curves at the two frequencies.

Three types of capacitors also were checked for the present paper (Table I). The values given depend as much on the capacitor construction as on the dielectric material.

The conclusion may be drawn from Table I that the change of frequency from 60 to 420 cycles produces a small effect upon corona-starting voltages.

Cables—Figures 2, 3, 4, and Table II

Five types of cable* were tested.

1. Number 16 (19/0.0113) Deltabeston (Flamenol, asbestos, and cotton braid over tinned copper—single conductor).
2. Number 8 (7/24/0.010) Deltabeston (Flamenol and cotton braid over tinned copper—single conductor).
3. Number 1/0 (19/55/0.010) Deltabeston (Flamenol and cotton braid over tinned copper—single conductor).

* Cable sizes given are American Wire Gauge numbers; the number of strands, the number of wires in each strand, and the diameter of each wire in inches are indicated in parentheses.

4. Number 12 (19/0.018) Deltabeston (Flamenol and cotton braid over tinned copper—three conductors).

5. Number 16 (26/0.010) household appliance cord, 220-volt (rubber and cotton braid over bare copper—two conductors).

Cables 1, 2, and 3 were tested in two electric-field configurations. Cable-to-cable tests were made by binding together two equal lengths of cable (Figure 2). The two ends of each wire were connected to one of the connecting spheres. This was done to insure against corona from the free ends. Cable-to-

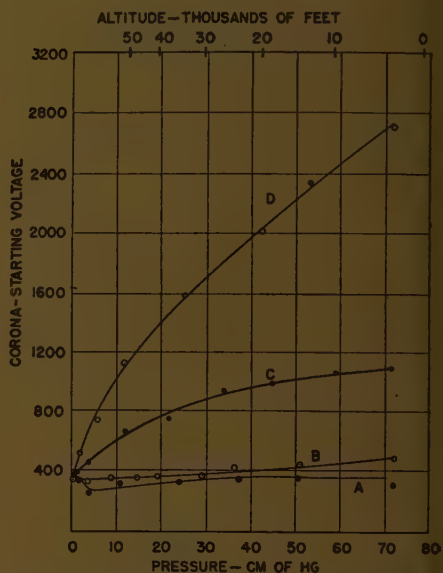


Figure 4. Effect of drying on the corona-starting voltages of number 8 cable

- Curve A—Cable to ground, 98 per cent humidity for eight hours
- Curve B—Cable to ground, room humidity
- Curve C—Cable to ground, vacuum dried
- Curve D—Cable to cable, vacuum dried

ground tests were run by laying a single large loop of the cable on a metal plane.

Cable 4 was a preconstructed cable with three insulated wires covered and bound together with an outer fiber wrapping. Two of the wires were connected together at one end and connected to the ground terminal of the corona detector. The third was placed at high potential. The three opposite ends were immersed in a small bottle of oil.

Cable 5 was the common 220-volt lamp and appliance cord.

Figure 3 shows cable-to-cable corona-starting voltages for cables with a moisture content as absorbed at room temperature and humidity. The term "room humidity" is not customarily used to describe the conditions of a test. However, under controlled humidities it took days for a cable to come to equilibrium. Wide variations in humidity

from day to day had small effect upon the corona-starting voltage. For reference, the average humidity for the three days in which the tests of Figure 3 were run was 76 per cent. The important points to notice are that corona never appeared below 300 volts and that the 220-volt lamp cord was decidedly superior to the airplane cables insofar as corona was concerned. The thicker insulation of the appliance cord was responsible for its high corona-starting voltage.

Figure 4 shows the effect of drying the number 8 cable by heating it under vacuum. The highest and the lowest curves on the graph were the extremes, the difference being a result of varying the moisture content from about zero to that absorbed in eight hours at 98 per cent humidity. The cables were stored and tested in desiccators, were kept dry by heat and a drying agent, or were kept at 98 per cent humidity by the presence of CaSO_4 and water.

The immersion in water of the number 8 cable-to-cable sample caused the corona-

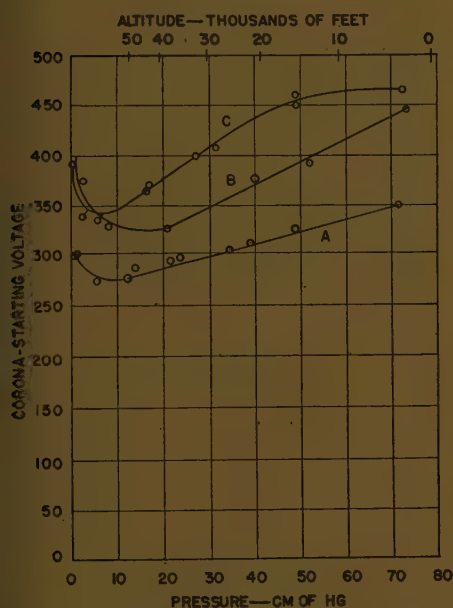


Figure 5. Corona-starting voltage of dry, nonhermetically sealed capacitors

Curve A—One-mil paper dielectric, not sealed or impregnated
Curve B—Two-mil paper dielectric, wax impregnated
Curve C—Two-mil paper dielectric, not sealed or impregnated

starting voltage to rise to 2,850 volts at 76 centimeters of mercury. This voltage was higher than the corresponding voltage on the dry-cable curve. It was seen that as the moisture content of the cables was increased the corona-starting voltages passed through a minimum.

A few points on the curve, taken at room temperature and pressure, are shown in Table II.

Although it is probable that the 300-volt point is not the exact minimum, altitude and pressure have small effect. Therefore, if the cable has functioned satisfactorily at similar humidities at low altitudes, these tests indicate that it will continue to function satisfactorily at high altitudes. All cables showed similar variations with moisture content.

Figure 4 shows the number 8 cable-to-ground corona-starting voltages. It would be expected from a consideration of the electric field that the values would be half those obtained when two cables were bound together. This was roughly the case when the cables were dry (compare curves D and C, Figure 4). However, at room humidity both curves dropped to approximately the same values.

Capacitors—Figure 5 and Table I

A number of capacitors were tested at variable pressure. Typical data are shown by the three curves of Figure 5. Curves A and C were taken on capacitors which were prepared in a manner

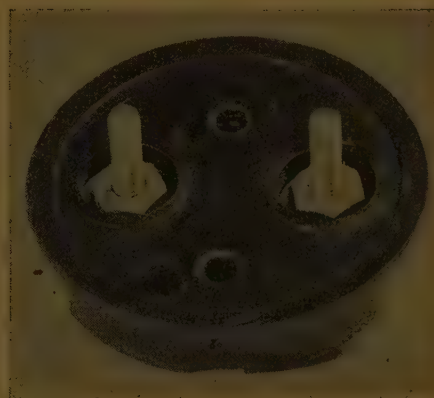


Figure 6. Meter-case back, two-inch diameter

to include the most air voids possible. The paper was dry and not impregnated. The rolls were loosened to permit complete evacuation of the interior of the capacitor. Curve B was taken as a typical wax-impregnated sample. Upon the reduction of pressure, as the breakdown strength of large air gaps dropped by a factor of five the breakdown strength of the air voids (the corona-starting voltages of the capacitors) dropped by as little as 20 per cent. The reason for this action is given at the end of this paper in the section on the dielectric strength of air.

In order that the effect of moisture could be studied, four of the unimpregnated roll capacitors were dried for 48

hours under vacuum and at 105 degrees centigrade. No change in the corona-starting voltages could be found.

It appears that the operating voltages of low-voltage capacitors which are not hermetically sealed and which are to be used at high altitude will not have to be decreased by more than 30 per cent from sea-level operating voltages even if the capacitors contain large air voids.

Meter-Case Back—Figures 6 and 7

A circular meter-case back (Figure 6) supporting two connecting bolts was

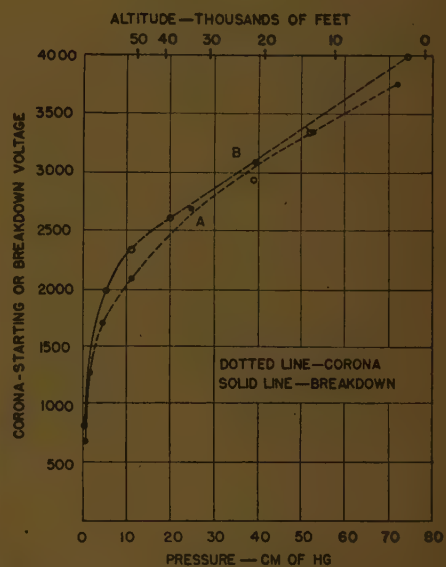


Figure 7. Corona-starting and breakdown voltage between bolts through the meter-case back of Figure 6

Curve A—Bolt heads not recessed
Curve B—Bolt heads recessed

also checked for corona. The bolts were mounted with an inch of separation between centers. In one test the heads and nuts were recessed; in the other they were mounted on plain surfaces. Because the curves for the two mounting methods are essentially the same, there is no advantage from the corona and the low-pressure arcover standpoint, in recessing the studs.

Toward the high-pressure end of the curve, the ionization did not occur along the surface of the base or through the air between the studs. This fact was ascertained by immersing the base and studs under oil after the data for Figure 7 had been taken. Under oil the same corona-starting voltage was found at room pressure as was found in air. In fact the same type of curve of corona-starting voltage versus pressure was traced down to about 30 centimeters of mercury. The ionization actually oc-

curred in air which was trapped in the space surrounding the studs where they passed through the insulation. At lower pressures the position of ionization shifted until breakdown appeared between the studs. Probably the point of this shift occurred at the knee of the curve.

Parallel Studs Through Plane Surfaces—Figures 8 and 9

Some additional data on studs through plane surfaces were taken. Number 4/40 studs were screwed into a one-half-inch insulating block (Figure 8). They extended one-half inch above the surface and were mounted perpendicularly in two spacings: one-fourth and three-eighths inch between threads. The leads were brought out under oil through the bottom of the insulated plate (Figure 8).

Figure 9 shows the curve of breakdown versus pressure. The only value of the corona-detection device in this test was to show that there was no corona before breakdown.

As corona was not involved, work along this line was thought to be outside of the scope of this report. Obvious weak points in the data were therefore not removed. For example, it was found that the breakdown voltage depended upon the sharpness of the edges at the top of the studs. The tip melting caused by one arcover with a 20,000-ohm resistor in series was sufficient to raise the breakdown voltage by 20 per cent. This effect probably is present in the data of Figure 9.

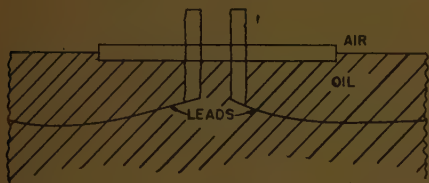


Figure 8. Parallel studs through insulating surfaces

The conclusion can be drawn that there will be no problem with corona on studs at practical spacings.

Needle Gaps—Figure 10

From the standpoint of corona, the worst electrode configuration that can exist is that of collinear needles facing point to point. For this reason number 8 needles at one-eighth-inch and one-fourth-inch spacing were checked for corona as a function of pressure. At high pressures corona occurred before breakdown; but, as shown on Figure 10, at low pressures

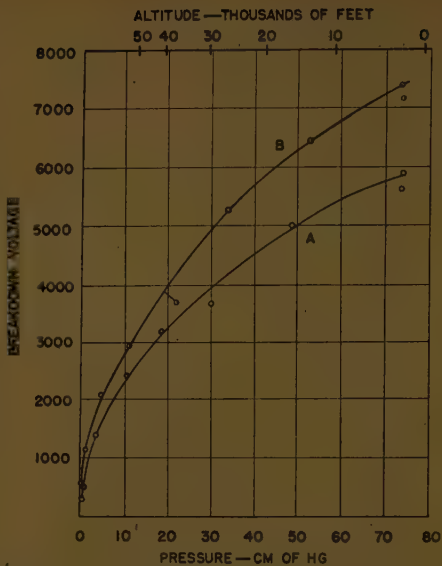


Figure 9. Breakdown voltage of the parallel studs of Figure 8

Curve A—One-fourth-inch spacing between threads
Curve B—Three-eighths-inch spacing between threads

breakdown occurred without first showing corona.

At high altitudes the random ionization is much greater than at sea level. To increase the number of ions in the test chamber, radium (1.8 micrograms) was placed four inches away from the gap. The effects of the radium were to reduce the time between pulses of corona, to reduce the short-time breakdown voltage of the gaps, and to make the breakdown and corona-starting voltage more exactly reproducible. All data were taken in one minute step-ups, the corona-starting voltages being defined as the voltage at which the first isolated pulses of corona occurred.

It may be concluded that at spacings above one-eighth inch no corona will be encountered in any electrode configuration at or near 208 volts.

Contamination of Surface Between Studs

Data were taken on the contamination of the plastic surfaces between the studs of Figure 8. The same conditions of test were used, care being taken to keep oil from the surface by cleaning with Solvaton. The object of this section of the work was to see if corona or high-frequency discharges could possibly be produced below 208 volts.

Data were taken with $\frac{1}{32}$ inch of dry dust lying on the surface. As in Figure 9, no corona appeared before breakdown, and the breakdown values were not lowered by the presence of the dust.

Table I. Corona-Starting Voltage of Capacitors at 420 Cycles as Per Cent of 60-Cycle Value

	60 Cycles (Per Cent)	420 Cycles (Per Cent)
Paper-Pyranol.....	100.....	95 to 90
Mica.....	100.....	91
Unimpregnated paper.....	100.....	105

The surface was then cleaned. An open pan of warm water was placed in the desiccator. The pressure was reduced to four centimeters of mercury where the water boiled freely, depositing a thick uneven layer of moisture on everything in the desiccator. High-frequency discharges appeared at from 500 to 700 volts as the pressure was varied from 2.4 to 74 centimeters of mercury. As the water evaporated from the surface, this discharge voltage rose to 1,700 volts at 74 centimeters.

At pressures above four centimeters, the steam soon cleared up. To produce vapor at all pressures, the principle of the Wilson cloud chamber was used. A small amount of tobacco smoke was blown into the desiccator to permit a cloud to appear as the pressure was reduced. Under these conditions the discharge voltage varied from 800 to 1,700 volts, at various pressures. No curve could be plotted because the pressure had less effect than did random changes in the moisture.

Finally, dust was added to the water on the surface, forming a mass of mud

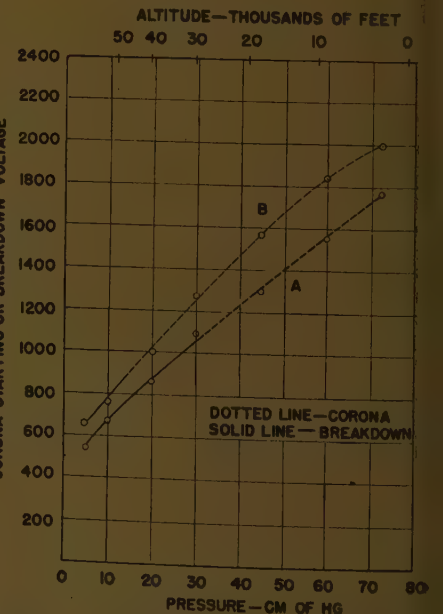


Figure 10. Corona-starting and breakdown voltage of needle gaps

Curve A—One-eighth-inch gap
Curve B—One-fourth-inch gap

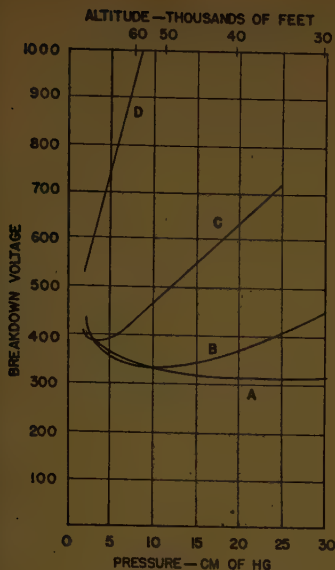


Figure 11. Breakdown strength of air at small spacings between rounded-edge, brass disks

Curve A—0.0004-inch gap
Curve B—0.002-inch gap
Curve C—0.008-inch gap
Curve D—0.040-inch gap

about $\frac{1}{32}$ inch thick. With this artifice, corona-like pulses appeared as low as 80 volts. A 4.5-volt Wheatstone bridge indicated a resistance of 74,000 ohms. Table III shows the type of variation found.

It is seen that these low values would probably cause trouble in the 208-volt system where they would not have affected the 28.5-volt d-c system. Because the effects of contamination were, as far as could be detected, nearly independent of pressure, it is probable that no corona difficulties will be introduced by the change from sea level to 50,000 feet.

The Dielectric Strength of Air as a Function of the Geometry of Electrodes

Figure 5 reveals an unexpected phenomenon. As shown by M. J. DeLerno,¹ the dielectric strength of air drops to one fourth of its sea-level value at about ten centimeters of mercury. However, the breakdown strength of the air gaps in

Table II. Corona-Starting Voltage of Number 3 Cable-to-Cable Sample Versus Moisture Content

Conditions	Corona-Starting Voltage
Dried by heat and drying agent.....	2,500
Room humidity.....	450
98 per cent humidity for eight hours.....	300
98 per cent humidity for 76 hours.....	1,400
Immured in distilled water one minute.....	2,800
Immured in distilled water 60 minutes.....	2,850

Table III. Effect of Water on Dust-Covered Surface

Pressure—cm of Hg.....	73.7..1.9..16.1..30.5..41.7..73.7
Corona-starting voltage..	192..130..125..137..105..80

the capacitors remained almost independent of pressure over this range. An examination of the literature of the sparking potential of air yields the following very probable reason for this apparent inconsistency.

In 1892 J. B. Peace,⁵ working with J. J. Thomson, obtained data for the curves that are replotted on Figure 11. On this graph it is shown that at very small spacings, such as at 0.0004 inch, the dielectric strength of air is not affected greatly by large changes of pressure. In fact the shapes of these curves are very similar to those of the corona curves of Figure 5.

Figure 12 shows the position of the air gaps where most corona occurs in capacitors. This position is known because corona markings are left on the paper. Below the corona-starting voltage the voltage across such a gap is a definite quantity, proportional to the total applied voltage and determined by the capacitor-divider effect of the dielectrics

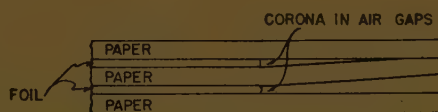


Figure 12. Section of capacitor showing position of corona at foil edge

in series. The gap is bound at each end by solid barriers and is subjected to an electric potential. The thickness of the metal foil is 0.0003 inch, and the breakdown path must be of comparable length. Therefore, the sparking potential of these gaps (and the corona-starting voltage of the capacitors) should, and do, show the same small dependence upon air pressure as did the 0.0004-inch and 0.002-inch gaps of Peace's data.

It becomes apparent that increasing the altitude has less effect upon the corona-starting and the breakdown voltages of small air gaps than large. The maximum effect of altitude is realized for large-plane parallel gaps where the pressure and the breakdown voltages are approximately proportional.⁸ The minimum effect of altitude is realized in small air voids, such as in capacitors, where the breakdown and the pressure are nearly independent. An intermediate case is shown in Figure 9 on parallel studs where the variation of breakdown is less than proportional to pressure. A

second intermediate case is shown by curve D, Figure 4, on dry cables. The air gaps between the cable insulations are relatively large in comparison with the capacitor air voids, and the corona-starting voltage is more dependent upon pressure.

An interesting fact found by Carr⁹ is that with uniform fields the sparking potential of air, regardless of its gap spacing, temperature, pressure, or random ionization, will never fall below 351 volts (the fields of Figure 11 were not quite uniform). Covering more recent work by various observers, Loeb⁷ makes the following statements: "A spark will not pass below about 275 volts in air no matter what the conditions. It is most important to realize that the minimum sparking potential exists and that below it a spark cannot pass. This fact is sometimes overlooked in practical application." By the word "conditions" he refers to the pressure, the temperature, the random ionization of the air, and the spacing and shape of the electrodes. If the temperature of the electrodes rises sufficiently to cause thermionic emission, such as in vacuum tubes or in restriking a-c arcs in circuit breakers, the air will permit the incidence of an electric current far below the 275 volts mentioned.

The voltages of this discussion are peak voltages. It is seen that neither corona nor breakdown will occur in air below about 195 volts rms.

An additional interesting point arises from the foregoing data. At high altitudes corona and breakdown in a capacitor which is safely rated for sea-level operations are more likely to occur around the bushings and internal leads to the

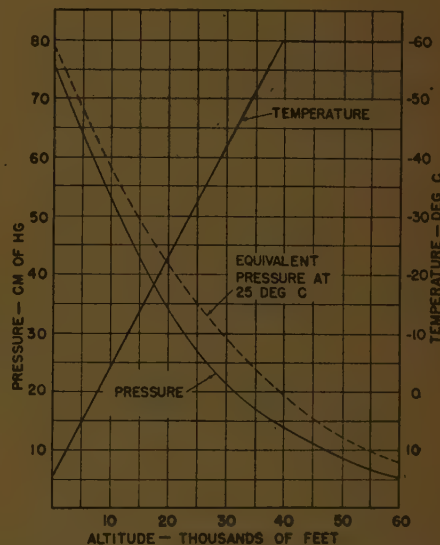


Figure 13. Change of atmospheric conditions with altitude

bushings than in the capacitor rolls. If the capacitor is completely filled with a liquid dielectric, or if it is gas filled and well sealed, the reduction of pressure with altitude will reduce the electric strength of only the external portions of the bushings. However, if the internal leads are in air and the pressure of that air drops with altitude, an unsafe condition may exist. Imagine a capacitor consisting of, for example, ten series sections of the roll of Figure 5, curve A. Even if the capacitor were not hermetically sealed, the corona-starting voltage of the rolls in series would remain fairly constant at about 3,000 volts, which is ten times the corona-starting voltage of the single roll. However, the breakdown voltage of the bushings and of the internal leads (if in air) would drop to below 351 volts if the pressure were reduced sufficiently.

Corrections for Low Temperatures at High Altitudes

High-altitude conditions were approximated by use of the data of Figure 13. The dotted portion of the temperature curve represents a rough average of the variable temperatures which occur in that region. No attempt was made to reproduce the low temperatures of high altitudes because Paschen's law, as stated by Cobine,⁴ makes it possible to perform tests in air at room temperature which are equivalent to tests at other temperatures. Paschen's law states mathematically that for any given electrode configuration, changes in the temperature and pressure of the air will not change the sparking potential (the writer adds corona-starting voltage) unless they change the density of the air. The density of the air is proportional to the ratio of pressure to absolute temperature, and if this ratio stays constant the density will stay constant also. Thus, two tests will be equivalent and will yield the same corona-starting or breakdown voltage in air if

$$Pa/Ta = Pe/Te \quad (1)$$

where Pa , Ta are the absolute pressure and temperature of the application conditions, and Pe , Te are the absolute pressure and temperature of the equivalent test.

All tests were run at about 25 degrees centigrade, or 298 degrees Kelvin ($Te = 298$). Therefore the corona or breakdown values for any electrode configuration in air at any altitude (or at any moderate

temperature and pressure) may be found from room temperature data by substituting in the pressure Pa and temperature Ta for that altitude in the following expression:

$$Pe = 298(Pa/Ta) \quad (2)$$

The corrected voltage can be taken from the room temperature curve at pressure (Pe). In this manner the curve of equivalent pressure at 25 degrees centigrade, plotted on Figure 13, was obtained. The equivalent altitudes shown on the graphs were, in turn, taken from this curve.

For example, at 35,000 feet the temperature averages minus 54.3 degrees centigrade, or 218.7 degrees Kelvin ($Ta = 218.7$). The pressure averages 18 centimeters of mercury ($Pa = 18$). The substitution of these values in equation 2 yields an equivalent pressure of 24.6 centimeters of mercury. The effect that this low-temperature correction has on corona-starting or breakdown voltages depends upon the shape and spacing of the electrodes. For large-plane parallel gaps, the change in voltage would be proportional to the change in pressure. The breakdown voltage would be increased by the ratio of 24.6 to 18, or by 36 per cent. On the three-eighth-inch parallel studs of Figure 9 the increase would be from 3,700 to 4,400, or by 20 per cent. In the capacitor of curve A, Figure 5, the increase would be from 285 to 292, or only 2.4 per cent. It is interesting to note that on curve B of Figure 5 and on curves A and B of Figure 11 the lowering of temperature at 60,000 feet decreases the corona-starting and breakdown voltages. Thus, it cannot be said that data taken at high-altitude pressures and at room temperature are always conservative, though this is usually the case.

Conclusions

1. Two tests revealed corona-like disturbances at voltages low enough to approach 208 volts. The tests were on moist contaminated surfaces and on moist aircraft cables. Therefore, conditions of high moisture in the 208-volt 400-cycle electric system should be avoided or investigated by means of life tests.
2. The low corona-starting voltages were nearly independent of pressure. Therefore, the change from steady-state operation at sea level to steady-state operation at 50,000 feet will produce no difficulties with corona in the proposed system.
3. The change in frequency from 60 to 400 cycles per second will produce no apprecia-

ble change in the corona-starting voltages of cables, air gaps, and capacitors. It very probably will produce no appreciable change in the corona-starting voltage of any electrode and field configuration in industry. (Figure 1 and Table I.)

4. M. J. DeLerno¹ has shown that the dielectric strength of air drops by as much as 75 per cent as the pressure is reduced from 76 to 8.7 centimeters of mercury (0 to 50,000 feet at 25 degrees centigrade). In this paper for the same change in pressure the greatest drop in corona-starting voltage (the breakdown of small air voids and gaps) was by factor of 71 per cent (Figure 4, curve D, cables). The smallest drop was by about 20 per cent (Figure 5, curve A, capacitors).

5. In the insulation of the aircraft cables the change in moisture content from a dry condition (Figure 4, curve D) to that assumed at room humidities (Figure 3, curve A) produced a drop in corona-starting voltage by as much as 84 per cent.

6. In low-voltage capacitors which are not hermetically sealed and contain air voids, it appears that the corona-starting voltage will not be reduced more than about 30 per cent even if the capacitors be elevated above 60,000 feet (Figure 5). No trouble should be expected from corona in the capacitor rolls at high altitudes, but the corona-starting and breakdown voltages of the bushings will be greatly decreased.

7. Tests were made with parallel studs extending perpendicularly from a clean insulating surface at spacings of one-fourth and three-eighths inch between threads. No corona existed before breakdown at pressures from 1 to 76 centimeters of mercury (Figure 9).

8. Between needle gaps the air would sustain steady-state corona without breakdown at high pressures. At low pressures, breakdown would occur without any sign of preceding corona (Figure 10).

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Polarized-Light Servo System

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Synopsis: A new servo system has been developed in which the connecting link between the primary and secondary shafts is polarized light whose plane of polarization rotates with the primary shaft. This makes possible the accurate following of the rotation of the primary shaft without any load being imposed on it. This servo system has been applied successfully in several electro-mechanical calculating machines.

SERVO mechanisms or follow-up systems are used in many recording and control devices to amplify small forces or torques so that the motion of a heavily loaded output mechanism will correspond closely to the motion of a very low torque input element.¹⁻³

Polarized-Light Follow-up System

In an electromechanical calculating machine, it was desired to control the motion of an output mechanism to cor-

3. It must operate to follow continuously the rotation of the wheel in either direction.
4. It must be able to follow rapid accelerations and decelerations of the wheel.

To fulfill these requirements, a servo system was developed which makes use of polarized light⁴ as the connecting link between the input and output mechanisms.

Principle of Operation

The principle of operation of the polarized-light servo system is shown diagrammatically in Figure 1. In this system a small integrating wheel rolls on the surface of a turntable, at an adjustable radius r .

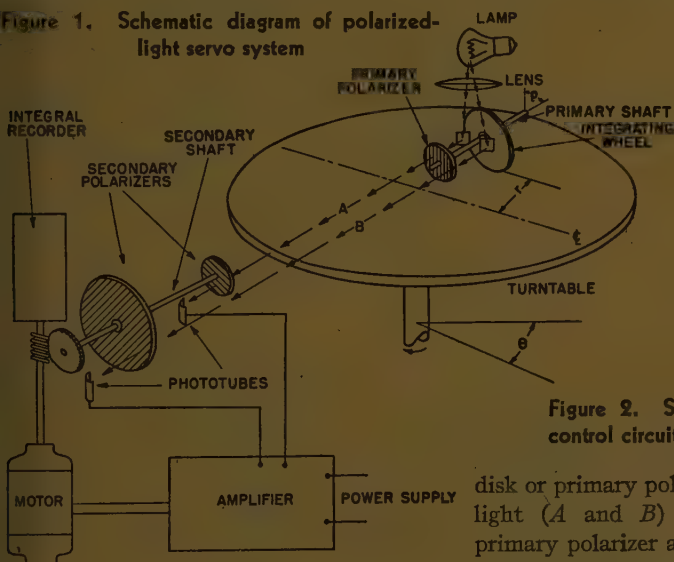
Attached to the same shaft (primary shaft) and rotating with this shaft and integrating wheel is a light polarizing

equal amounts of light will strike both phototubes. If the plane of polarization is not at 45 degrees to both secondary polarizers, unequal amounts of light will strike the phototubes. Thus, if the primary polarizer is rotated from balance a small amount in one direction, the light on one phototube is reduced because the angle between the two polarizers in that beam becomes more nearly 90 degrees; at the same time, the angle between the planes of polarization in the second beam becomes more nearly zero, with a corresponding increase in light on the second phototube. If the primary polarizer is rotated in the other direction, the light beams are unbalanced in the other direction.

The unbalanced output of the phototubes is amplified and controls the speed and direction of rotation of the servomotor, and thereby the secondary shaft and polarizers, to keep the light on the phototubes always at or near balance.

There are four positions of the primary shaft with respect to the secondary shaft where the light beams may be balanced. Only two of these positions, however will give a condition of stable balance.

Figure 1. Schematic diagram of polarized-light servo system



respond closely to the rotation of a small integrating wheel which rolled on the surface of a revolving turntable.

The requirements, not fully met by existing follow-up systems, were:

1. The follow-up system must impose no load or restraint on either the integrating wheel or its bearings.
2. It must permit free axial movement of the wheel.

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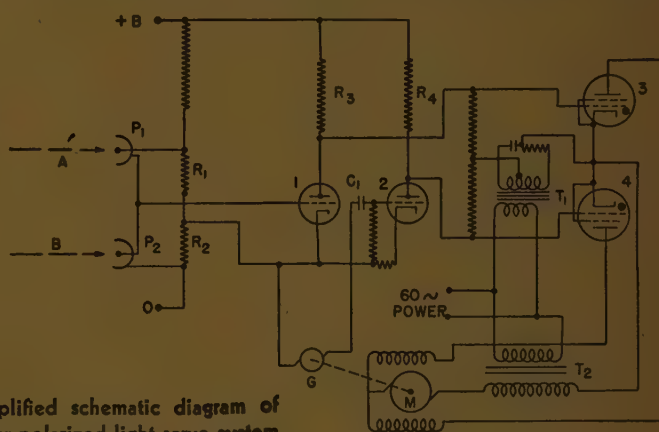


Figure 2. Simplified schematic diagram of control circuit for polarized-light servo system

disk or primary polarizer. Two beams of light (A and B) passing through the primary polarizer are polarized similarly, and the plane of polarization rotates as the primary shaft rotates.

A secondary shaft is, in effect, coupled to the primary shaft by means of these two rotating beams of polarized light in the following manner. The two beams of light fall on two phototubes after each has passed through a separate secondary or control polarizer. These two secondary polarizers are attached to the secondary shaft in such a manner that their planes of polarization are at right angles to each other.

When the primary polarizer is oriented so that its plane of polarization is half way between, or at an angle of 45 degrees with both of the secondary polarizers,

Once the condition of stable balance has been established it is maintained, and the secondary shaft will rotate with the primary shaft in either direction within the allowable limits of speed, acceleration, and load as determined by the motor and amplifier characteristics.

The axis of the primary shaft is held by bearings parallel to the plane of the turntable surface. For changes in radius of contact of the integrating wheel, the primary shaft and polarizer can be moved axially along the two light beams without materially affecting their balance.

Electronic Circuit

Figure 2 is a simplified schematic diagram of the control circuit. The two light beams fall on phototubes P_1 and



Figure 3. Polarized-light servo system for integrating pressure traverse recorder

P_2 which form two legs of a bridge circuit comprised of R_1 , R_4 , and the resistances of the two phototubes. The voltage unbalance of this bridge is applied between grid and cathode of vacuum tube 1. This tube together with tube 2 and resistances R_3 and R_4 form a second bridge circuit whose output is applied to the grids of two thyatron tubes 3 and 4.

The anode currents of the thyatrons, supplied from the 60-cycle power source through transformer T_2 , flow through a split field series motor to control its speed and direction in response to unbalance of the light beams A and B .

A small d-c generator is attached to the shaft of the motor, and its output voltage is applied through a capacitor C_1 between the grid and cathode of tube 2. The voltage e generated by this generator is proportional to the speed ω of the secondary shaft. For the frequencies encountered, the current through C_1 , and therefore the voltage across the grid resistor of tube 2, is proportional to de/dt and is therefore proportional to $d\omega/dt$ the acceleration of the output shaft. Thus, the condition of balance of the two light beams is anticipated, and the system is stabilized and remarkably free from the hunting or oscillation commonly experienced in servo systems.

It will be noted that a single lamp is used as a light source for both beams of light so that any changes in the light output due to aging, darkening of the bulb, and input voltage affect equally the light falling on both phototubes, causing no unbalance of the system. The bridge circuits employed also make the electronic circuits relatively free of unbalance because of supply voltage fluctuations.

The torque-angle characteristics of the polarized-light servo system are dependent on the characteristics of the amplifier and motor. Within operating

limits the torque is approximately proportional to the relative angular displacement of the light polarizers at any given speed. Series-motor characteristics make possible very high torques for rapid acceleration and deceleration. No accurate measurements of maximum accelerations and decelerations have been made, but it is estimated that the primary shaft can accelerate or decelerate at 2,000 rpm per second or more before the secondary shaft will drop out of synchronism. Speeds as high as 1,500 rpm have been used, but this is not necessarily the upper speed limit.

The secondary shaft will follow the primary shaft in angular position with an accuracy of plus or minus one or two degrees. This accuracy will be affected by nonuniformity of polarization in the polarizers and nonuniformity of light transmission through them. Since the

primary and secondary polarizers normally operate at 45 degrees to each other, the rate of change of light transmission with respect to angular displacement is a maximum. Therefore, the angular errors due to variations in the polarizers are at a minimum.

Applications

INTEGRATION

The polarized-light servo system is being used successfully in new electromechanical instruments for solving accurately problems involving integration. Refer to Figure 1; the radius r at which the integrating wheel rolls on the turntable is variable by means of a cam or screw and represents the integrand.

If θ is the angular displacement of the turntable, the angular displacement of the integrating wheel and primary shaft ρ is proportional to $\int r d\theta$.

$$\rho = k \int r d\theta$$

The angular displacement of the secondary shaft is the same as that of the primary shaft and integrating wheel, and since considerable power is available to drive this shaft, it can be loaded to drive other calculating and recording mechanisms. The primary shaft is held in alignment by jewel bearings and is balanced so that radial and thrust loads are substantially zero. Since there can be no restraining torque on the primary shaft because of loading of the secondary shaft, the integrating wheel rolls on the turntable with negligible slippage and correspondingly high accuracy.

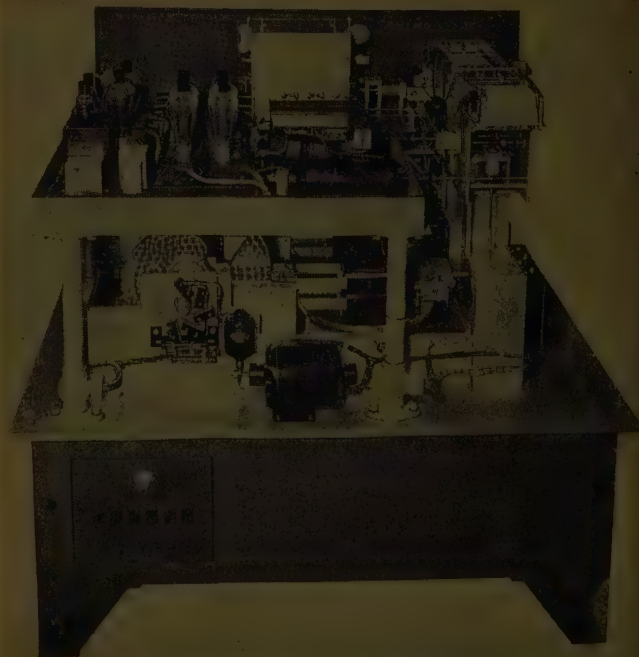


Figure 4. Integrator unit (without cover) for automatic integrating pressure traverse recorder. Rear view

Figure 3 shows a polarized-light servo system as used in the new General Electric integrating pressure traverse recorder, a specialized calculating machine which employs two follow-up systems as integrators. The phototube amplifier is tuned down to show its construction and the secondary polarizers.

The secondary shaft is at right angles to the primary shaft, and the light beams are changed in direction by means of mirrors. The phototube amplifier for the second integrator is shown at the lower right in operating position.

Figure 4 displays the same machine which shows the cams for moving the integrating wheels on the turntables. The driving motors and thyatron controls are on the shelf above the turntables and cams.

Figure 5 is a front view of the calculating and recording unit of the integrating pressure traverse recorder which is used by the research section of the



Figure 5. Integrator unit for automatic integrating pressure traverse recorder

General Electric turbine engineering division in its air test laboratory for studying flow phenomena through turbine passages. In this machine the integrated values will check each other within 0.01 per cent on repeated integration of the same function. These errors can be due largely to mechanical tolerances. This indicates that the slippage of the integrating wheel on the turntable is extremely small.

A special integral recorder on this device makes possible the reading of integrated values to the precision required for such measurements.

Figure 6 shows the General Electric differential analyzer⁶ which is used in solving problems involving the use of differential equations. This machine has fourteen integrating units, each with its polarized-light servo system.

SPEED MEASUREMENT

In another application a variation of this servo system has been used to measure accurately over a wide range the speed of a large rotating machine. The turntable is driven at a constant and accurately known speed by a synchronous motor from a regulated frequency source. The secondary polarizers are driven by the machinery whose speed is to be measured and the wheel is positioned on the turntable so that it follows the secondary polarizers; thus the radius of the wheel on the turntable is an accurate measure of the unknown speed. Speed measurements have been made to 0.025 per cent accuracy for primary shaft speeds up to 1,300 rpm.

DIFFERENTIATION

In the measurement of speed as already described, the servo system is actually used as a differentiator in which the angu-

lar displacement of the secondary polarizers ρ' may be expressed by the equation:

$$\rho' = \int \omega_1 dt$$

where ω_1 is the angular velocity of the control polarizers.

The angular displacement of the primary polarizer ρ is expressed by

$$\rho = k \int r d\theta$$

$$d\theta = \omega_2 dt$$

where ω_2 is the angular velocity of the turntable.

$$d\theta = \omega_2 dt$$

If $\rho = \rho'$, then

$$d\rho = d\rho' = \omega_1 dt = k\omega_2 r dt$$

and

$$\omega_1 = \frac{d\rho'}{dt} = \frac{d\rho}{dt} = k\omega_2 r$$

Since ω_2 is constant,

$$\frac{d\rho'}{dt} = Kr$$

When used as a differentiator, the servo system is inherently oscillatory, but by taking the proper steps the oscillations can be highly damped.

Conclusions

The new servo system using plane polarized light as the interconnecting link between the primary and secondary mechanisms makes possible the driving of heavy loads with accurate following of primary shaft without imposing any restraint or reaction upon its motion, either in the direction of rotation or axially.

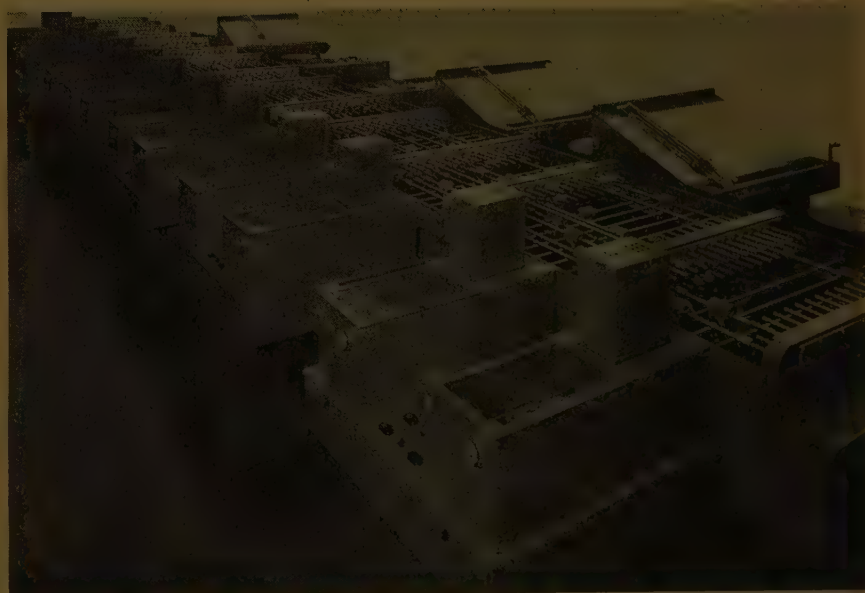


Figure 6. Differential analyzer showing 14 integrator-unit assemblies

Electric-Circuit Burning-Clear and Damage Phenomena on Aircraft Structures

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Synopsis: Normal and continuous performance of electric circuits is a prerequisite to the effective use of airplanes. Electric short circuits which result in the loss of power for vital control operations or which cause fires are definite hazards. The extensive use of the 28.5-volt d-c aircraft systems, the proposed 120-volt d-c system, and the consideration being given a three-phase 120-208-volt a-c grounded neutral system for high-altitude planes necessitated an investigation into the burning-clear and damage phenomena on aircraft circuits. Short circuits were applied on an aluminum-alloy section of an airplane, and oscillograms of short-circuit current and voltage taken. In both the a-c and d-c systems it was found that the fault-damage and burning-clear phenomena depended upon the energy level in the short-circuit area. When the contact area between the conductor and aircraft structure was small, the energy level was high, and the fault burned itself clear. In such cases the aircraft structure was perforated. Increase in contact area and a consequent reduction in energy concentration resulted in a sustained fault current. In some of these cases a definite welding of the conductor to the aircraft structure occurred, while in others no burning took place.

The General Problem

It is generally accepted that the correct performance of the electric system is vital to the effective use of an airplane. Electric-wiring faults, such as short circuits resulting from gunfire or other causes, may result in faulty control or fire hazard. Experience has shown that on

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the commonly used 28.5-volt d-c systems such short circuits are often self-clearing, and serious consequences do not result. However, this is not always the case, and it is possible that a significant number of airplanes have not returned from the combat area because of damage to the electrical system. Accordingly, it was felt advisable to investigate the conditions under

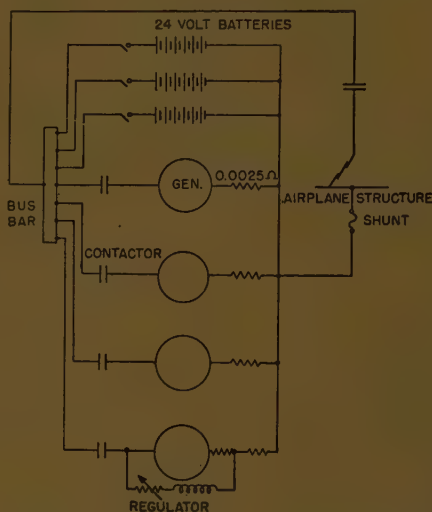


Figure 1. Aircraft electrical system as adapted for burning-clear tests

which faults may be expected to clear and to determine the magnitude of current and length of time required to cause serious damage to the aircraft structure when a short circuit occurs. It should be recognized that, in practice, where circuit protection is used the fault duration and damage may be limited by this protective equipment which would remove the faulty circuit from the system. Such

protection was not used in the tests as they were intended to show the effects of a short circuit where system protection was not involved. Circuit protection is discussed in a companion paper.¹

Since consideration is also being given to a three-phase 120-208-volt 400-cycle a-c grounded neutral system (120 volts to ground), and to a 120-volt d-c system similar investigations using such power systems were carried out.

The Investigational Method

The basis of the investigation was a series of direct full power short-circuit tests made in the laboratory with a portion of aircraft structure as test piece. A diagram of connections of the circuit for the 28.5-volt d-c system is given in Figure 1. This circuit is an adaptation of a typical electric circuit for a four-engine airplane such as the "Flying Fortress" and is, as nearly as is possible, a duplicate of the actual system. Each of the four P1 aircraft generators (200 amperes 28.5 volts) was driven by a ten-horsepower 3,600-rpm induction motor supplied from a variable frequency source. The negative terminal of each generator was connected through a resistance of 0.0025 ohms

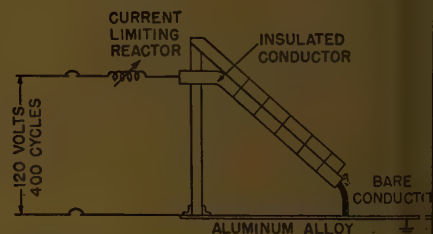


Figure 2. Arrangement of test sample for single-phase-to-ground 400-cycle burning-clear tests

ohm to a common point, while the positive terminals were tied to a single bus. Three batteries could be paralleled with the generators by means of single-pole switches. Time, current, and voltage values for each short circuit were determined by means of an automatic magnetic oscillograph.²

As a test specimen representative of aircraft structure, part of a wing section and nacelle of a "Flying Fortress" was used. To this was attached the negative terminal of the supply system. The positive terminal of the system was connected through a contactor to a length of 11 aircraft cable, one end of which rested perpendicularly on the aircraft structure. Short circuits were applied by closing the contactor. The position of the conduct

Several applications have been made in integrating and differentiating unit of special electromechanical calculating and measuring devices for solving complicated problems accurately and quickly.

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as chosen because cables running parallel to the aircraft fuselage and subsequently covered by gunfire can be bent so as to contact the structure perpendicularly. The effects of a short circuit brought about in this way are the most severe.

With the generators operating at 3,000 rpm and an open-circuit voltage of 28.5 volts, and at first with no batteries in the circuit, short circuits as previously mentioned were applied to various sections of the aircraft structure by closing in the line contactor. The supply system was then augmented by the battery, then two, and finally three batteries in parallel with the generators and the tests repeated.

structure and cable were covered with a bell jar which was evacuated to a pressure corresponding to the required altitude.

Data on the 120-208-volt a-c system were obtained in the course of separate tests in which power was obtained from three single-phase transformers supplied by means of a motor generator set. A diagram of connections for single-phase-to-ground faults is given in Figure 2. Variations in current level were obtained by means of taps on air-cored reactors connected in series with the transformer and by connecting two or three transformers in parallel. The current range investigated was selected to cover the possible number and sizes of generators operating

altitude of 40,000 feet, and to generator end shields of magnesium alloy.

Analysis of Results

Both the d-c and a-c tests brought out very decisively that there are two widely different results of short circuit; these are referred to in the following as "self-clearing" and "weld." By the former is meant melting and vaporizing of the metal in the vicinity of the short-circuit area and its explosive expulsion from the arc, resulting in a complete clearance of the short circuit. A weld takes place when only sufficient energy is involved in

Table I

Test	System	Number of Generators	Number of Batteries	Current (Amperes)	System Condition Prior to Short Circuit	Type of Material	Cable Size (Number)	Insulation	Altitude	Results
Short circuit	28.5-volt direct current	Four	None	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	One	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Two	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	Loaded	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	No load. Resistance added to external circuit	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	28.5-volt direct current	Four	Three	Up to 4,500	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston, glass-cotton, 100 per cent glass	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt direct current	—	—	Up to 2,000	No load	0.020-inch to 1/8-inch Al (alloy)	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt 400 cycles alternating current	—	—	Up to 2,500	No load	0.016-inch to 1/4-inch Al (alloy)	16 to 1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt 400 cycles alternating current	—	—	Up to 2,500	No load	0.010-inch Mg	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	120-volt 400 cycles alternating current	—	—	Up to 2,500	No load	Mg end shields	1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Short circuit	208-volt 400 cycles alternating current	—	—	3,700	No load	Copper to copper	16 to 1/0	Deltabeston	Sea level and 40,000 feet	Self-clearing and sustained
Gunfire	24-volt direct current	—	1,500 amperes capacity	Up to 1,500	No load	0.016-inch to 1/8-inch Al (alloy)	16 to 1/0	Deltabeston, glass-cotton, 100 per cent glass	Sea level	Self-clearing and sustained

A considerable number of tests was carried out with three batteries in the system, and the effects on the short circuit of load on the system, of increased short-circuit resistance, and of simulated high altitude were investigated. For the altitude tests a small section of 0.020-inch aluminum alloy and a piece of 1/0 cable touching the alloy perpendicularly were set up on a platform to which supply terminals had been connected. The

in parallel on certain aircraft systems.

Using 0.020-inch and 0.25-inch aluminum alloy, short circuits as in the foregoing were applied at different current levels and with various sizes of conductor. Similar tests were carried out in a steel chamber evacuated to a pressure corresponding to an altitude of 40,000 feet. Further short circuits were applied to 0.10-inch magnesium alloy, at sea level and at a pressure corresponding to an

the short circuit to result in a permanent connection between the conductor and airplane structure.

Oscillograms representative of self-clearing and weld faults are given in Figures 3 and 4, respectively, for the d-c system, and in Figures 5 and 6, respectively, for the a-c system. Figure 7 shows the progress of a typical short circuit while Figure 8 is illustrative of the damage to the aircraft structure as a re-

sult of short circuit. Table I summarizes the test program and test results.

28.5-VOLT D-C SYSTEM

(a) *Effect of Batteries.* Although the electric supply system of the "Flying Fortress" airplane consists of four generators and three batteries in parallel, it was felt advisable to study the effect of varying the number of batteries. The results here compared with the general trend of results throughout all the tests. Whenever the contact pressure between the cable and aircraft structure was such that only a few strands of the cable touched the aluminum alloy, whether the latter were skin, bulb angle, or rib, the

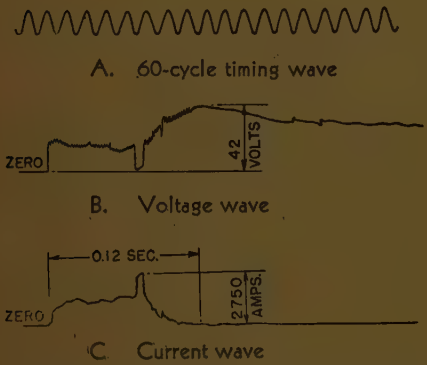


Figure 3. Oscillogram showing self-clearing d-c fault
Time of short circuit 0.12 second. Maximum current 2,750 amperes. Maximum voltage 42 volts

fault was self-clearing and often accompanied by heavy arcing and explosive scattering of molten aluminum-alloy particles. In most cases the fault did not burn clear until the structure was perforated. However, there were instances when the cable melted at a sufficiently high rate to open the circuit before the perforation was complete.

With the pressure between the cable and airplane structure such that the contact arc was large, the short circuit was continuous and did not burn clear. In some cases a weld was produced while in others there was no visual damage either to cable or aircraft structure. As the number of batteries increased, a greater pressure was required to produce a short circuit which would not burn clear.

When the contact is light, only a few strands of cable form the short circuit with the airplane structure. Thus at the instant of establishment of the short circuit, the concentration of energy is

extremely high, causing the copper and aluminum alloy to melt superficially and an arc to strike. This arc continues until the fault clears either because of a structural perforation, or because of rapid melting of the cable.

If the contact pressure between cable and structure is high, the contact area is much larger and, therefore, the energy concentration greatly reduced. In general this energy concentration is insufficient to cause initial melting of the cable or aluminum alloy, and no arc results; the fault is continuous and sustained. The ampere capacity of the system increases with an increase in the number of batteries and, therefore, for the short-circuit energy concentration to be maintained at a level low enough to cause continuation of the short circuit, a greater pressure is required for each battery addition. Thus a system having a small ampere

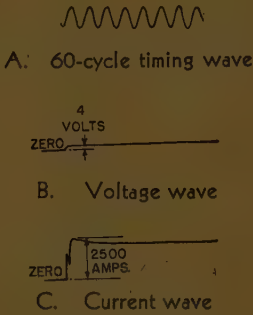


Figure 4. Oscillogram showing d-c short circuit resulting in weld
Maximum current 2,500 amperes

capacity will probably produce more welds due to short circuit than one with a large ampere capacity, since less pressure is required in the former case.

The oscillogram of Figure 3 is illustrative of a self-clearing fault. The effect of the field regulator can be seen during arcing periods, the generator voltage rising with current flow. Rapid and irregular variations in the voltage wave, caused by abrupt changes in resistivity within the arc and movement of the cathode spot, are plainly visible. When the current reaches its final zero and the fault clears, the rise of recovery voltage and its slow decay to normal open-circuit value are clearly recorded.

An oscillogram characteristic of a short circuit resulting in a weld is given in Figure 4. After the initial peak the current assumes its steady-state value, and no arcing takes place.

(b). *Effect of Load on System (Four Generators, Three Batteries).* When the system is loaded prior to the application of the short circuit, the values of

short-circuit current, the resulting damage both to cable and structure and the time of short circuit are in general the same as for four generators and three batteries in parallel without load. The peak value of the short-circuit current is reached more quickly after short circuiting, however, by virtue of the fact that with load on the system the main field strength is high and the armature current is already about one fifth of the value of short-circuit current.

(c). *Effect of Increased Short-Circuit Resistance.* The effect of increasing the short-circuit resistance was similar to lowering the ampere capacity of the electric system. Thus with higher values of resistance the possibility of a weld is increased. Faults remote from the airplane bus are therefore more likely to result in a weld because of current limitations due to increased circuit resistance.

(d). *Effect of Altitude.* At pressures corresponding to higher altitudes arcing persisted somewhat longer, al-

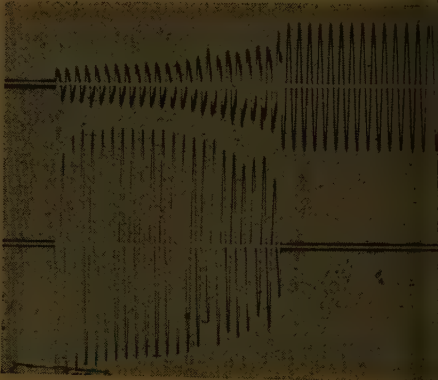


Figure 5. Oscillogram showing self-clearing a-c fault
Time of short circuit 0.052 second. Maximum current 2,000 amperes. Maximum voltage 120 volts
Upper curve—Voltage
Lower curve—Current

though current and voltage values were about the same as those obtained at sea level. Increasing contact pressure between the cable and airplane structure resulted again finally in a weld. When the short circuit resulted in perforation of the aluminum alloy the hole was more clear-cut than at sea level due to decreased oxidation. The molten alloy was scattered with explosive violence in a direction perpendicular to the structure and away from the conductor, but there was little evidence of molten copper. No appreciable change in pressure inside the bell jar was noticed during each short circuit.

120-VOLT D-C SYSTEM

Exploratory tests at sea level and a pressure corresponding to an altitude of 10,000 feet with a 120-volt d-c system were carried out. The results followed the same trend as those obtained with the 120-208-volt d-c system and the 120-208-volt a-c system, faults either burning clear or resulting in a weld, the governing factors being as stated previously. In some cases arcs approximately half an inch long were obtained.

120-208-VOLT A-C SYSTEM

(a). *Phase-to-Ground Fault on Aluminum Alloy, at Sea Level.* With a supply system of 120-208 volts alternating cur-

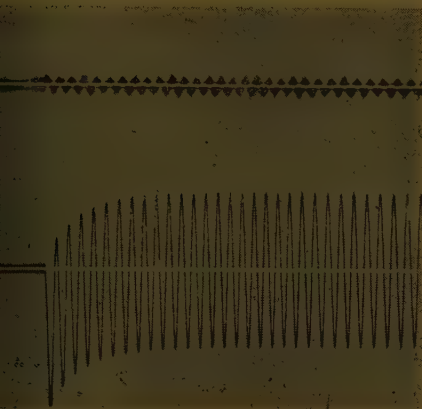


Figure 6. Oscillogram showing a-c short circuit resulting in weld

Maximum current 670 amperes

Upper curve—Voltage

Lower curve—Current

ent, the effects of short circuit again fell into the two categories—self-clearing and weld. When the contact between the conductor and airplane structure was light, and therefore the contact area small, whatever the size of conductor, type of structure, or current level involved, the fault was self-clearing, and an arc formed. In all cases the arcing was severe, though rarely prolonged, and was accompanied by explosive scattering of molten metal. Small fires were started within a radius of ten feet from the short-circuit area, the test floor being covered with a thin layer of sawdust and some oil. Faults which were not self-clearing fell into the second category of a "weld or sustained short circuit." In these instances the material, or the shape of the part of the aircraft structure concerned, was not important, the principal factors being the current level and cable size.

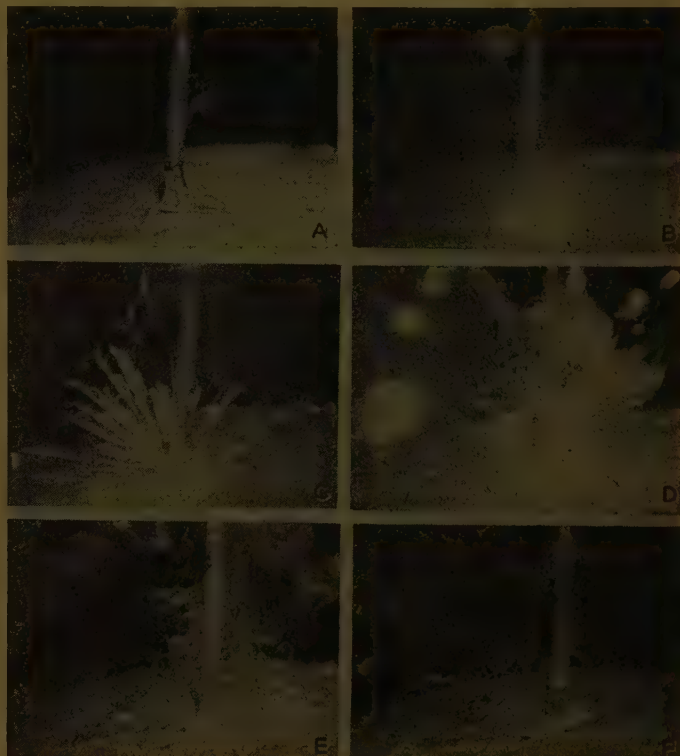
Thus, for a given current level, the smaller the conductor the greater is the contact pressure required to produce a weld. For a given conductor size, in order to produce a weld, the contact pressure required is much less the lower the current level. Short circuits occurring in remote sections of an aircraft electric circuit may readily result in welds or be sustained, unless the fault was otherwise interrupted. Figure 8 illustrates damage from short circuit to a section of an

airplane with the damage caused by gunfire.

Further bullets were fired so that they would strike a conductor on the entering side. In such cases a self-clearing short circuit occurred when the conductor contacted the structure as the former swung back into position after being severed by the bullet impact.

Whenever a conductor was severed by gunfire, about one inch of insulation was torn off on both sides of the break, and the

Figure 7. Progress of short circuit resulting in perforation of aircraft structure



airplane. The damaged area identified by the number 8 is representative of a short circuit resulting in a weld while the remaining areas are perforations from self-clearing faults.

Gunfire Tests

Parallel conductors were mounted inside and one inch from an aircraft section and connected at one end to a bus fed from a 24-volt battery. The other ends of the conductors were insulated and the aircraft section connected to the negative terminal of the battery. With a range of approximately 100 yards, 50-caliber-machine-gun bullets were fired at the test piece so that they would strike the conductor on the leaving side. In almost every case faults were produced and in one instance, as shown at A in Figure 9, the conductor welded to the structure. Damage both to conductor and structure, due to short circuit, was insignificant in com-

parison with the damage caused by gunfire. Although in general only a few strands subsequently formed the short circuit, in one instance most of the cable cross section contacted the aircraft structure. In this case a weld was produced, as stated previously.

Three small areas of the aircraft section were covered with a thin coat of insulating varnish. In these areas faults occurred only when a severed conductor contacted the edge of a perforation produced by gunfire.

General Interpretation

The physical aspects of the d-c and a-c short circuits were similar, and pictures shown in Figure 7 serve to illustrate the progress of a self-clearing short circuit on either system. Evidence of explosive scattering of molten metal in Figures 7e and 7f, just before the fault clears, indicates that the formation of the perfora-



Figure 8. Electric-fault damage to aircraft structure

- 3,4, and 5—Self-clearing fault. 1,120 amperes, number 16 cable
 6—Self-clearing fault. 2,000 amperes, number 8 cable
 7 and 9—Self-clearing fault. 665 amperes, number 8 cable
 8—Welded fault. 665 amperes, number 8 cable
 11 and 12—Self-clearing fault. 1,970 amperes, number 8 cable

The increase in measured voltage indicated in the oscillogram of Figure 5 is due to a slight increase in arc length.

(a) *Phase-to-Ground Fault on Aluminum Alloy, at High Altitude.* Both the self-clearing and weld type of short circuit were substantially independent of barometric pressure corresponding to

high altitude. The duration of the former type was generally the same as at sea-level pressure, and the extent of damage was unchanged except for decreased oxidation at high-altitude pressures. Because of this the perforations were more clean-cut than at sea-level pressure.

(b) *208-Volt Phase-to-Phase and Three-Phase Faults.* Phase-to-phase faults on various sizes of wires and three-phase faults fell into categories of self-clearing and weld, the current level and contact pressure affecting both as before. In those instances when the fault cleared the conductor melted back into the insulation until the voltage could no longer maintain the arc. The insulation was not damaged severely. When the fault was not self-clearing, the cable became overheated and would be severely damaged unless the fault were cleared by other means. Results at high altitude pressure were similar.

(c) *Phase-to-Ground Fault on Magnesium Alloy, at Sea Level and High Altitude.* Two forms of magnesium alloy were used, the first being 0.10 inch thick with a painted surface finish and the second an aircraft generator end shield.

The insulating properties of the painted surface finish on the former were sufficient to prevent an arc from striking when voltage was applied. However, when this surface finish was removed over a small area and the conductor applied there, a short circuit occurred with results similar to those for aluminum alloy both at sea level pressure and in a rarefied atmosphere. The magnesium-alloy plate did not ignite, but burning particles were scattered explosively and continued to burn for some time.

Similar results were observed with the magnesium-alloy end shields.

In all tests on the magnesium alloy the current level was maintained at approximately 2,000 amperes.

Résumé of Results

The general phenomena of burning, clear and welding as presented in the foregoing admit of further statements as follows on particular aspects of the short circuit problem.

1. When the energy concentration at the fault is high (high current, low contact area) the short circuit is generally self-clearing. Thus, the higher the current level the greater is the likelihood that faults will burn clear. There would be less danger of a weld due to the higher contact pressure required.

2. Fault damage to the aircraft structure was similar for the 28.5-volt and 120-volt d-c systems as for the 120-208-volt a-c system. However, on the a-c and 120-volt

Transmission and Relaying Problems on the Fort Peck Project

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THE recently completed Fort Peck power plant with its substation and transmission facilities has several features which are unique and of particular interest. This paper will point out application problems and their solution in connection with power transmission and relaying.

The initial installation of generation at Fort Peck consists of one 38,888-kva 13.8-kv 128.5-rpm three-phase 60-cycle water-wheel generator. Ultimately, two more generators are to be installed, one a duplicate of this first unit and one smaller unit. The substation is located on the west bank adjacent to the powerhouse and at present has one large transformer bank consisting of three 16,667-kva single-phase transformers stepping up to 161 kv from generator voltage. A 15,000-kva three-phase shunt reactor is installed on the 13.8-kv bus just ahead of the power transformers. All switching, except for transmission-line disconnects, is performed at generator voltage, and all power circuit breakers are of the compressed-air type.

The only high-voltage transmission associated with this initial installation is the one 161-kv line extending to the Rainbow substation bus of the Montana Power Company at Great Falls, Mont. The total length of the line is 288 miles; it is of H-frame construction, and the conductor employed is about half 477,000-circular-mil steel-reinforced aluminum

cable and about half 300,000-circular-mil copper. The line was built originally to feed power to the dam site from Great Falls for use during construction.

At the Montana Power Company, terminal of the 161-kv line, a bank of three 20,000-kva single-phase three-winding autotransformers step down to 105 kv for connection onto the Rainbow bus at that voltage. At this location switching is performed at 105 kv. The power transformers at both ends of the line have the neutral solidly grounded on the high-voltage winding.

Figure 1 shows a simplified one-line diagram of the Fort Peck installation, transmission line, and receiver system. This sketch includes the system elements which will be discussed specifically in subsequent paragraphs, and most of the equipment shown has been described previously.

The unusual length of the transmission line involved introduces interesting application problems. This line length, coupled with hydrogeneration, immediately suggests a study of transient-stability limits for faults occurring on the Montana Power Company system at or near the Rainbow substation bus. Because of the very great shunt capacitance inherent to a single line section of nearly 300 miles, problems concerning open-circuit voltages and synchronizing are of importance. Also, because of line length, relaying presents a special set of conditions which standard high-speed impedance relays cannot meet. The salient factors affecting these problems and the measures considered in reaching the solutions will be examined.

General-System Studies

The a-c network calculator was employed in studying the general system shown in Figure 1. The relative simplic-

ity would permit manual calculations with reasonable accuracy, but the use of the calculator permitted complete study, including numerous points too time-consuming by manual methods.

Four variations of the system finally adopted were studied, and these four connections are shown in their bare essentials in Figure 2. Note that the principal difference lies in transformers and shunt-reactor application. Henceforth, these four systems will be referred to as systems *a*, *b*, *c*, and *d*.

Of interest is the fact that all four of these systems operate satisfactorily in the steady-state condition, that is, from a standpoint of load and voltage regulation. The differences appearing in voltage levels at the two load buses in the different systems always can be compensated adequately by control of excitation at the two terminals. The resultant exchange of reactive is sometimes objectionable for other reasons, but in the steady-state case it is always operative. The principal reason for considering the unusual voltage ratios of systems *c* and *d* that result in a "sloping" voltage characteristic was to study the possible advantage of accepting excessive line drop in a very long line under load and adjusting normal transformer ratios a full-voltage class to meet it. The inherent decrease in line-charging kilovolt-amperes is a further advantage. Generally, the disadvantages accruing from reduced voltage level outweighed advantages in the cases studied. These relative merits will be discussed more specifically in following paragraphs.

Synchronizing

The charging kilovolt-amperes of the 288-mile transmission line, when operating at 161-kv, is approximately 43,000 kva. Since the generator rating at Fort Peck is 38,888 kva, it is impossible to charge the line at normal voltage in the connection of system *a*, unless part or all of the charging capacity is supplied from Rainbow. This presents an operating inflexibility, since it is impossible to synchronize at normal voltage at Rainbow.

By adding the 15,000-kva shunt reactor and obtaining system *b*, sufficient

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Figure 1. Simplified one-line diagram of Fort Peck system connection

line charging is canceled to permit the Fort Peck generator to "pick up" the line, and synchronizing can be accomplished at either terminal. Furthermore, when the line is energized from Rainbow, this shunt reactance cancels almost all of the voltage rise inherent to the line, so that only about three per cent differential exists across the synchronizing breaker (31 per cent for system *a*).

The sloping line-voltage characteristic of system *c* inherently reduces charging current to a figure of 38,000 kva but still does not permit synchronizing at Rainbow, since the generator charging capacity does not equal this figure, and because a voltage differential of 50 per cent exists across the synchronizing breaker at Rainbow. Such a voltage differential might be objectionable because of the large surge of reactive current that would occur immediately subsequent to closing the breaker. The sloping voltage characteristic presents ideal synchronizing conditions across the open switch at Fort Peck if the line is charged from Rainbow. The rising voltage characteristic very nearly follows the intentional "uphill slope," so that only seven per cent voltage differential from normal exists, a figure that could be met easily by generator regulation or be ignored altogether.

System *d* presents practically the same case as system *c* with respect to synchronizing, except that the line charging is further reduced by reduced voltage to a figure of 23,000 kva. The Fort Peck generator easily can supply this quantity, but the voltage differential across the open switch at Rainbow is then 66 per cent, an excessive figure.

System *b*, comprising full 161-kv voltage operation with a 15,000-kva shunt reactor, presents the most flexible case for system interconnection initiated at either terminal.

Stability

Since only a single-circuit line interconnects Fort Peck with the Montana Power Company, the tie is severed subsequent to each transmission-line fault, and there is no transient-stability limit. Transient stability becomes an important consideration, however, for faults and switching on the Montana Power Company system. Numerous high-voltage

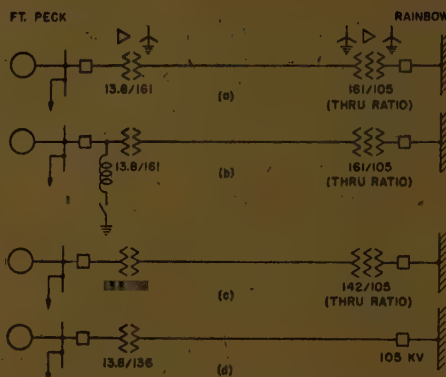


Figure 2. Variations of system studied

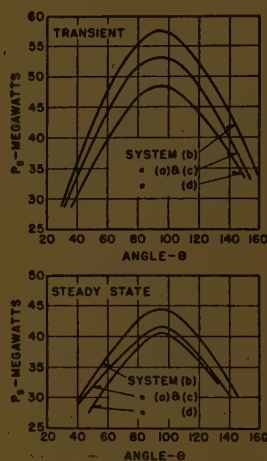


Figure 3. Power-angle curves for the systems studied

P_s = power output—Fort Peck generator
 θ = angle between internal voltages

circuits emanate from the vicinity of the Rainbow bus, and, if Fort Peck were to swing out of step for faults or switching on these circuits, the effectiveness of the interconnection would be impaired seriously. For this reason stability was studied for faults on this adjoining system.

Power-angle curves applying to the different systems studied are shown in Figure 3. Note that system *b* offers a substantial increase in stability over the other systems studied, as demonstrated by the power-angle relations. All systems maintain stability for switching operations on the Montana system, and all systems are stable for single line-to-ground faults occurring near the Rainbow bus and cleared in relaying and breaker times actually obtaining on the Montana systems. System *d*, employing lower-voltage transmission, presents a marginal case for single line-to-ground faults, and

this was one of the considerations that led to its discard. None of the systems studied are stable for multiphase faults near the Rainbow bus, although angle-time curves indicate that system *b* may provide a stable solution for many multiphase faults that occur some appreciable distance beyond the interconnecting point.

Of unusual interest is the fact that systems *a* and *c* show identical power-angle characteristics. This is a function of the large line-charging kilovolt-amperes in comparison with total generation that exists in this installation. If the voltage is lowered somewhat, line charging is reduced enough to permit the Fort Peck generator to operate at a lagging power factor and, of course, at a high internal voltage. This increase in internal voltage completely offsets the increased equivalent line impedance inherent to the lower-voltage operation.

The increase in stability with system *b* is due solely to the 15,000-kva shunt reactor which permits generator operation in the lagging range. The power-angle curves for the steady-state case (Figure 3) show that system *b* will be operating at 79 per cent of the steady-state limit when full-load kilowatts (35,000) are generated. It was believed that operation at above 85 per cent of this limit was likely to be unsafe during system disturbances, and this is borne out by the transient solution that indicates system *d* to present marginal stability for single line-to-ground faults beyond Rainbow. Systems *a* and *c* eliminate this uncertainty, but the considerable extra margin provided by system *b* for relatively small investment was believed good insurance.

Water Rheostat

The water rheostat was necessitated by the omission of the surge tanks because of wartime conditions. The original

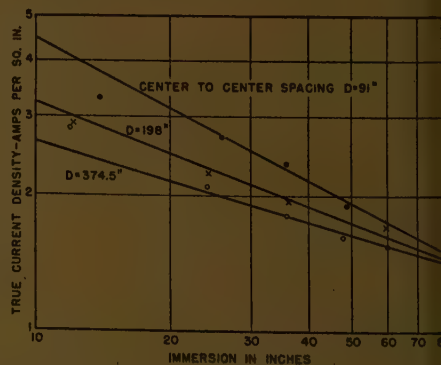


Figure 4. Results of field tests on water rheostats

Four-inch outside-diameter electrodes
 13.8 kv

plans provided for installation of three surge tanks of adequate size to provide satisfactory hydraulic stability and capacity for the ultimate installation of three units, with each surge tank connected to its individual penstock by a suitable riser. The surge rise and water-hammer pressure increases were computed on the basis of using a five-second governor time for full-opening and closing the turbine wicket gates. However, it was deemed inadvisable to use large quantities of critical steel plate for this project just after the entry of the United States into the war, and the contract, therefore, was canceled.

ACTUAL WAR INSTALLATION

The completion of part of the power development was authorized subsequently, with the surge tanks omitted.

The omission of the surge tank for the installed unit developed the following conditions:

1. The governor time would have to be slowed down materially to avoid subjecting the tunnel, penstock, and turbine to excessive water-hammer pressures.
2. Involuntary rejection of line load due to line faults, or other reasons, would result in runaway of the unit unless measures were taken to avoid this.

Various schemes were investigated then with the view of securing smooth transition from steady line-load conditions to steady local-load.

The most promising of these schemes appeared to be the use of a water rheostat to replace temporarily the line load with an automatic arrangement for reducing the rheostat load by withdrawing the electrodes from the water, so that the unit could be transferred smoothly from the more or less heavy line load to the light local load. A detailed investigation of this procedure convinced the

authors that such operation might result in hydraulic instability, taking the form of a series of governor swings of increasing intensity with unpredictable results.

We, therefore, suggested that, on the occurrence of a line fault and loss of line load, the unit be brought down automatically to the speed-no-load position and that the water rheostat be set at a fixed value and used only as a brake to avoid runaway speeds. A tank rheostat was installed in the powerhouse to provide for the suggested service.

The following provisions were planned to avoid runaway conditions as far as possible:

1. The line-breaker tripping relay was arranged to energize the rheostat-breaker closing mechanism and also to trip the governor speed-no-load solenoid, so that the governor would act to reduce the gate position to approximately speed-no-load position irrespective of speed changes. The rheostat load would be tripped off then by a suitable mechanism, the various adjustments being made in such a way that the unit would continue to run after the gate movement was completed but at speed approximately normal.
2. The electrical arrangement was such that the line breaker would open and the rheostat breaker would close on either of the following eventualities:
 - (a). Fault on the line.
 - (b). Opening of breaker at receiving end of line.
3. An electrical fault in the generator itself results in the field being opened and precludes the possibility of placing an electric load on the machine. In such case, the generator differential relays will act to trip the governor shutdown solenoid, causing the gates to close to the fully closed position. There is no method of avoiding a runaway speed under these conditions.

WATER-RHEOSTAT TESTS

As stated previously, the water-rheostat tank in the powerhouse was designed for braking service only and was not

suited, therefore, for carrying current continuously for testing purposes. To obtain information on the effect of variations in electrode spacing, size, and immersion, as well as for applying a steady load on the turbine during certain hydraulic tests, a temporary rheostat was rigged in the tailrace. The electrode size could be varied from $2\frac{3}{8}$ to 8 inches outside diameter, the immersion from zero to six feet, and the spacing from about 7 to about 30 feet. The voltage also could be varied from zero to 13.8 kv. The resistivity of the water was approximately 590 ohms per inch cube at 15 degrees centigrade and was found to vary with temperature according to the following formula:

$$\rho = \frac{820}{10^{0.0001t}}$$

where

ρ = resistivity in ohms per inch cube
 t = temperature in degrees centigrade

The test results were reduced to terms of current density in amperes per square inch, as it was realized that limitation of current density was an important factor in successful operation. A few tests were made with twin electrodes, but it was soon apparent that the behavior of these was exceedingly complex, and the majority of tests was made with 4-inch and $8\frac{5}{8}$ -inch outside-diameter electrodes

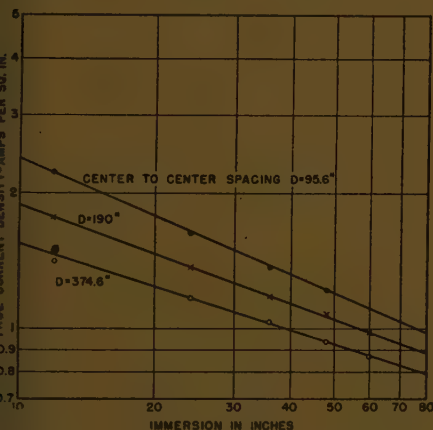


Figure 5. Results of field tests on water rheostats

$8\frac{5}{8}$ -inch outside-diameter electrodes at 13.8 kv

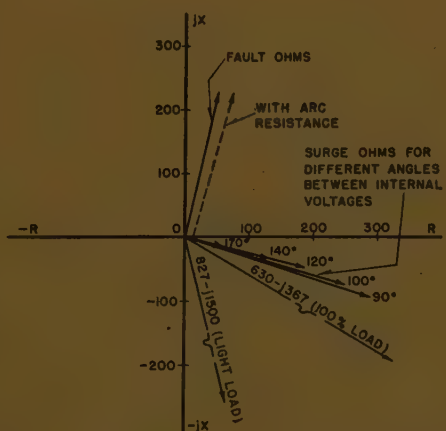


Figure 6. Impedance values as seen by relays at Fort Peck

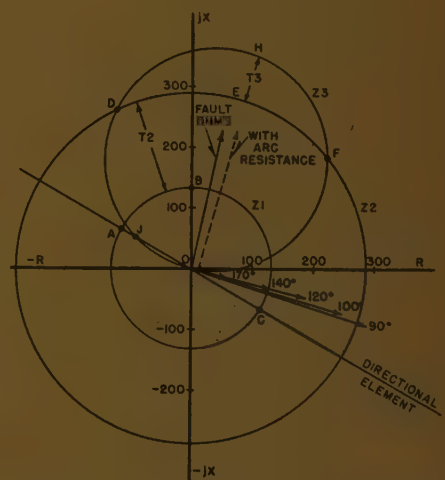


Figure 7. Distance-relay characteristics at Fort Peck

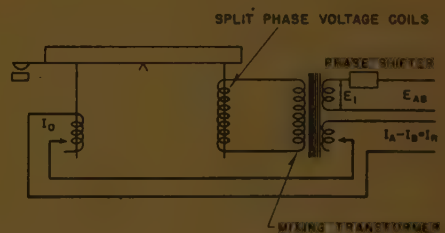


Figure 8. Schematic diagram of beam impedance element with modified characteristic

3. For a given immersion (within the range tested) current density decreases as spacing increases.

Several tests were made by rejecting various line loads to various rheostat loads, and it was found that a suitable selection of rheostat loads could be made which would result in reasonable pressure changes in the penstock and reasonable speed changes of the machine, so that the test showed that the wooden tank in the powerhouse, when provided with the proper electrodes, will prove adequate for rejection at periodic intervals of loads of 15,000 kw and higher with the operating procedure as recommended. It was found impractical to build a water rheostat of large enough proportion that would be suitable for continuous operation or to be used for loads smaller than 15,000 kw.

Transmission-Line Relaying

With the construction of the Fort Peck line in 1934 it became evident, because of the small difference between load currents and fault currents, that proper

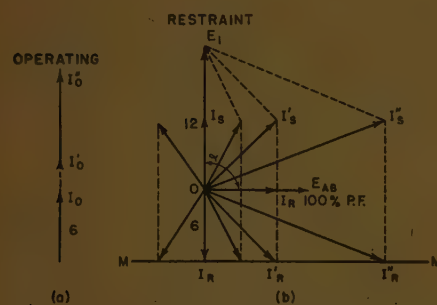


Figure 9. Vector diagram of current and voltage forces acting on the beam

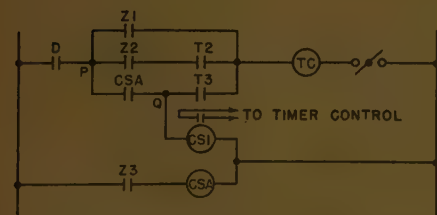


Figure 10. Schematic trip-circuit connection

protection could be provided only by zone-type distance relays, and, therefore, impedance-type relays were selected. Whereas there was little difference between the load-current and fault-current magnitudes, there was a wide difference in their phase-angle positions. Accordingly, the phase-angle characteristic of a standard impedance relay was accentuated and shifted to the proper operating zone by manipulation of the capacitor potential devices, and these relays have given very satisfactory service for several years. It is believed that this was the first instance of the application of a phase-angle discriminating feature to a distance relay in order to cope with the conditions on an extremely long transmission line. However, with the addition of the generating equipment at Fort Peck, the conditions with which the distance relay must cope have changed, and it has become desirable to extend further the phase-angle discriminating capacity of the impedance relays.

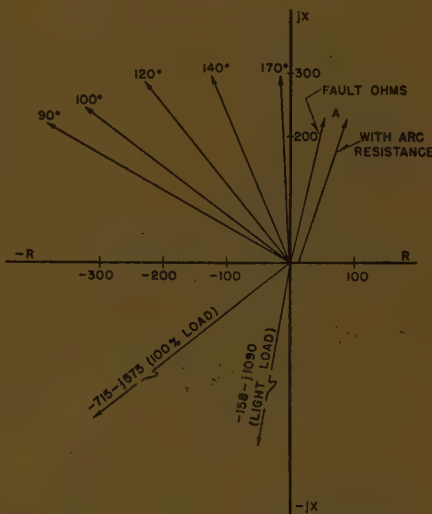


Figure 11. Impedance values as seen by relays at Rainbow

The new conditions presented to the relays are the presence of synchronizing surges on which relay action is not desired until the surges approach actual out-of-step conditions. The conditions as an impedance relay located at Fort Peck sees them, are shown in Figure 6 which gives the magnitude and phase angle of the impedance ohms which are presented to the relays. The impedance vectors, designated by angles from 90 to 170 degrees, represent the ohm values as seen by an impedance relay obtaining its current and voltage from the 161-kv line at Fort Peck for different angles between the internal voltages at Fort Peck and Rainbow, as indicated. In

may be noted that the maximum load-ohm vector is considerably longer than both the fault-ohm vector and the surge-ohm vectors, and, therefore, a standard impedance relay could be set to trip for faults but not for load currents. However, it has been determined that the system can experience surges up to 130 degrees between internal voltages and still recover synchronism after an external fault is cleared. If the internal voltages at Fort Peck and Rainbow deviate more than 130 degrees, actual out-of-step conditions are reached, and the line must be opened. It is clear from Figure 6 that a standard impedance relay, when set to trip for faults at Rainbow, will trip also for surge conditions from which the system can recover, since the surge-ohm values are too close to the fault-ohm values.

It was desired to have at Fort Peck a relay characteristic which would provide instantaneous tripping for faults over a portion of the line, time-delay tripping for faults over the remainder of the line with time-delay backup tripping for faults beyond the Rainbow terminal, and instantaneous tripping on swings beyond a 130-degree angle between internal voltages. This tripping characteristic is depicted in Figure 7. Instantaneous tripping is provided by the impedance element $Z1$, and the directional element over the area bounded by the points A , B , 140 degrees, C , and O . A second impedance element trips in the area bounded by the points O , J , D , E , and F . This second element trips through a timer, the operation of which is controlled by the directional element and a third element $Z3$. The $Z3$ element is a modified impedance element which operates for any impedance vector that terminates inside the circle O , J , D , H , F .

To change the characteristic of a beam-type impedance element into a displaced circular characteristic, as shown, no change in the beam element itself is required. Figure 8 shows schematically a beam element with the familiar split-phase voltage restraint on the rear end of the beam and a current coil on the front end. The restraint end of the beam, instead of being supplied with voltage only, is supplied with the vector sum of a current and voltage. The delta current $I_A - I_B$ is supplied to a primary winding of a transformer, while the voltage E_{AB} is supplied through a phase shifter to another winding. The secondary winding feeds the standard split-phase voltage coils. The current $I_A - I_B$ also flows to a current coil on the contact end of the beam.

The action which takes place to cause the element to have a circular characteristic can be seen from the vector diagram in Figure 9. This is drawn for the case where the center of the circle is to be placed on the X axis and passed through zero. The current I_R in the transformer winding is in phase with the voltage E_{AB} at 100 per cent power factor, but the voltage E , applied to the other winding is shifted 90 degrees leading. The operating energy on the front end of the beam is represented by the vector I , although this is the same current as that operating on the rear end of the beam. While the current on the front end is shown as a vector, no vector relationship exists between the pull on the front end and the pull on the back end of the beam, since the beam has substantially no response to the phase angle between the forces on the two ends. It is arranged that the current I_0 produces a mechanical force on the front end of the beam equal to the force produced by the current on the back end of the beam when no voltage is present. For fault currents lagging 90 degrees it is easy to establish the conditions for a balance point. For instance, if the voltage E_i is assumed to be 12 units, then it is evident that the current I_R directly opposite must be 6 units in order for the net restraint of 6 units just to balance an operating force of 6 units. If the current lags the voltage less than 90 degrees (say I_R'), it must be increased to a value such that the vector sum of I_R' and E_i (or I_S') still equals I_R' , because the operating current I_0 has increased at the same rate, in order to maintain a balance point. It can be seen from an inspection of Figure 9 that the current I_R and I_0 for any angle must terminate on the straight line MM in order to make the scalar value of the vector sum $E_i + I_R = I_S = I_R = I_0$. In other words, the line MM represents the locus of balance currents for a given voltage E_i . Division of the voltage E_i by the balance currents gives impedance values, which plotted on R and X co-ordinates gives a circle with its center on the X axis and passing through zero. The center of the circle can be placed on any other axis by regulating the angle α between E_i and E_{AB} . For instance, if α is less than 90 degrees, the circle center is at a point between the $+X$ and $-R$ axes; if α is between 90 and 180 degrees, the center is between the $+X$ and $+R$ axes.

The aforementioned element follows the equation $EI \cos(\alpha + \theta) = E^2$, and such a characteristic has been used for a number of years in connection with an induction element. It may be noted,

however, from the equation that, for close in faults where E approaches zero, the energy in the element also approaches zero resulting in sluggish indecisive action. It is interesting to note that a beam element following this same law is not operating under a low-energy condition. On the contrary, since heavier currents are obtained for close-in faults on long lines, the energy in the beam is even greater when the voltage is zero. Positive high-speed operation, therefore, at zero voltage is readily obtained by very slightly increasing the current pull on the front end of the beam with respect to the current pull on the rear end.

RAINBOW RELAYS

The ohmic picture presented to the relays at Rainbow on the 105-kv bus is

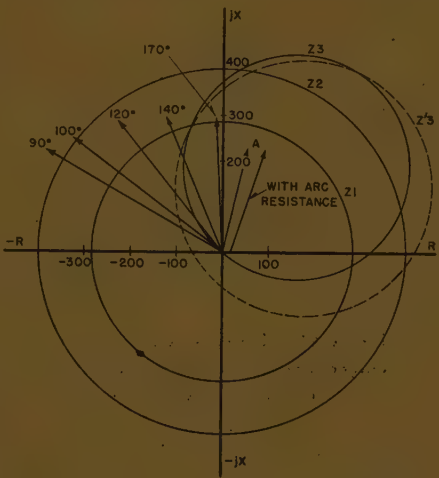


Figure 12. Distance-relay characteristics at Rainbow

shown in Figure 11. Here the only requirement is that the relay characteristic distinguish the surge ohms through 130 degrees and the load ohms from the fault ohms. Figure 12 shows the characteristic chosen. Here, however, it was desired to set Z1 element well into the transformer bank at Fort Peck with Z2 set beyond the low-voltage bus and Z3 even farther. Because of the long setting on Z1 element, and also to take care of possible future increases in the capacity at Rainbow, it was considered desirable to supervise the Z1 element through the Z3 element. This was done by moving the Z1 trip connection from point P to point Q on the schematic diagram in Figure 10. Placing the Z1 element effectively in series with the Z3 element means that the Z1 element can no longer trip independently for close-in faults, and the Z3 element must operate positively for all faults. As mentioned previously, the beam element possesses

plenty of energy for faults giving zero voltage; even though its characteristic circle passes through zero. The element, however, possesses an additional advantage in that a definite margin of safety can be attained. This is done by passing the circle beyond zero as shown by the dotted circle Z'3 of Figure 12. This is accomplished very easily by increasing the current force on the front end of the beam in relation to the current force on the restraint end of the beam. The amount that the zero point is projected into the circle is regulated by the excess force on the front end of the beam as compared with the current force on the back end, and is accomplished very readily by manipulation of the current taps and core screw on the front end of the beam. The diameter of the circle, or the ohm setting, is regulated directly by manipulation of the current taps on the beam and on the transformer-primary current coil in unison, keeping the relative ampere turns constant.

With only a single high-voltage line involved, no high side switching is employed, and the differential relaying on the two terminal transformer banks cannot isolate low side faults. The impedance relays described will isolate

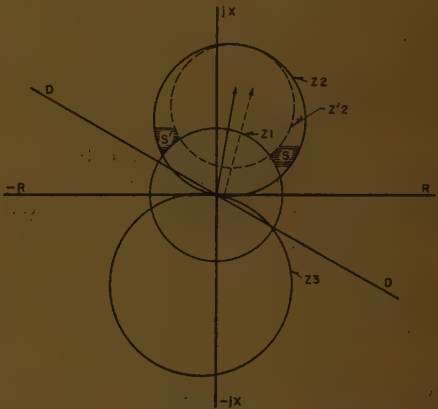


Figure 13. Distance-relay characteristics for carrier-current operation using four elements

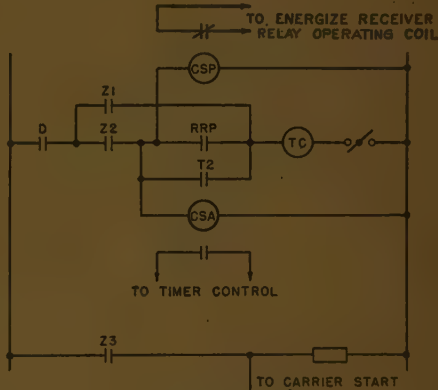


Figure 14. Schematic trip connections for relays in Figure 13

promptly in each case phase faults occurring at the far end of the line, but ground faults will not be handled if they occur on the low-voltage side of the transformers. For this reason the differential relays at each location are arranged to trip

suitable for long lines. Figures 13 and 14 show one possible combination. Carrier is started for external faults by the Z3 element with a displaced circular characteristic. Instantaneous tripping independent of carrier is provided by the directional element *D* and the Z1 impedance element over a portion of the line. Carrier tripping over the whole line is provided by *D* and Z2 element with a displaced circular characteristic, while backup time tripping beyond the

are regulated as before by the current taps on the operating and restraint ends of the beam. It is, therefore, evident that the circles Z1 and Z'2 can be positioned, so that tripping on severe synchronizing surges is prevented, but adequate coverage of the fault-ohm area is obtained.

Since the characteristic circle of the beam element can be adjusted to any diameter and its center placed anywhere with respect to the *R* and *X* axes, another combination is suggested using even less elements. This is depicted in Figure 15 where the circles of Z1 and Z2 overlap to provide good coverage in the range of the fault ohms, restriction in the range of load current and surges, and also coverage for external faults. Carrier is started by Z1 and Z2 and is removed by *D*, Z1, and Z2 elements which also provide a time-delay backup. Complete carrier and backup protection, as far as the distance relay is concerned, is thus accomplished with only three elements per phase.

Conclusions

The further extension of the phase-angle discriminating feature of the impedance relays, which have provided protection for the Fort Peck line since 1934, has enabled this same type of relay to accommodate the more severe conditions imposed by the addition of generating capacity at Fort Peck.

The addition of the movable circular characteristic to a beam-type impedance relay, with the easy ability to regulate the diameter and position of the circle, has opened up new possibilities in the protection of electrically long lines without the necessity of increasing the number of relay elements.

The use of shunt reactors to equalize voltages and increase transient-stability limits will increase as long line sections at very high voltages become more prevalent.

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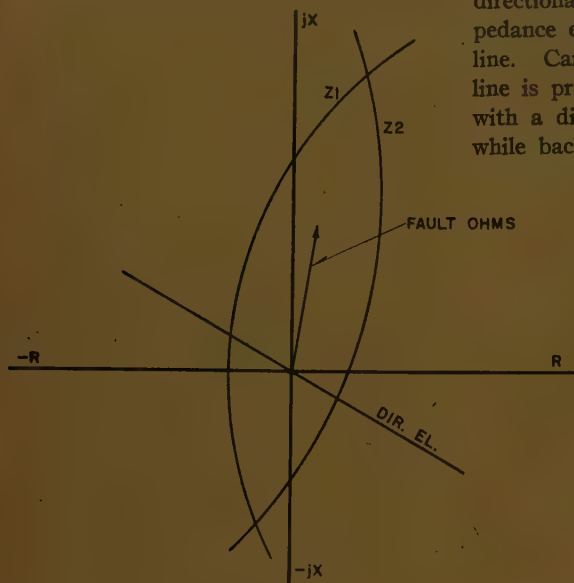


Figure 15. Distance-relay characteristics and connections for carrier-current operation using three elements

a three-phase grounding switch; an artificial phase fault is thus created; and the impedance relays clear promptly. These two grounding switches are shown in Figure 1. At Rainbow a high-voltage spring-closed switch is used, while at Fort Peck an existing 15-kv breaker is used.

Carrier-Relay Schemes

While carrier-relay operation was not involved on the Fort Peck project, it is interesting to see how the characteristics discussed previously could be fitted into a carrier scheme. There are several ways in which the standard three-zone impedance relay can be provided with various combinations of characteristics and be used in a carrier arrangement

line is provided by *D*, Z2, and T2 elements.

In some cases it may happen that the maximum swing conditions from which the system may recover involve minimum ohmic values for which tripping is not desired in the general region *S* and *S'*. The Z2 element can be made unresponsive to these surge-ohm values without changing its response to fault ohms by contracting the circle into the position shown by the dotted circle Z'2. It may be recalled that the zero point on the *R* and *X* diagram definitely can be placed inside the circle by overbalancing the current force on the front end of the beam. Conversely, the zero point definitely can be excluded from the circle by underbalancing the front-end current force. The diameter and position of the circle

Steady-State Stability of Synchronous Machines as Affected by Voltage-Regulator Characteristics

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STEADY-STATE stability of synchronous machines is an old subject, and the fact that voltage regulators may on occasion increase the stability limit is more or less well known.¹ The present paper, however, aims to contribute to the knowledge of the subject by:

(a). Presenting a method for calculating directly the gain in steady-state stability with a given regulator and excitation system and also for predetermining the optimum regulator and excitation-system characteristics to give maximum gain in stability for a given synchronous machine or set.

(b). Presenting the results of calculations by the methods developed for certain typical systems so as to give some notion of the possible gains under various conditions.

The relations developed may be used to study the effects of regulator and machine characteristics, power factor, regulator location, and so forth. An important application of the analysis is the case of electric ship propulsion, where the size and weight of the generator and motor are in part determined by the steady-state stability characteristics. The method of analysis consists in first setting up the transient equations of the system, then considering small displacements from any given equilibrium condition. The equations for small displacements are linear and may be tested directly for stability.

Conclusions

From the results shown here, and from additional calculations which have been made, the following conclusions may be stated:

1. A properly designed voltage-regulating system can increase the steady-state stability limit of a synchronous machine by a considerable amount.
2. Fast regulator and exciter action and low transient reactance are desirable. On the other hand, the amplification factor of the regulating system must be co-ordinated properly with the machine and system constants rather than made as large as possible.
3. The possible gain in power limit for two synchronous machines is considerably

greater than for a single machine connected to an infinite bus through a tie line.

4. Amortisseur windings have little effect on the possible gain in power limit.

5. Although the exact value of exciter time constant is not important, additional lags in the regulating system should be avoided, as they reduce the gain considerably. Some exciter time lag actually may be beneficial in increasing the permissible range of regulator amplification.

6. For maximum gain in power limit, a regulator with broad regulation and rapid response should be used. A very slow droop-correcting device could be used to maintain constant voltage over a range of load.

7. A regulator stabilizing transformer has little effect on the maximum gain but can permit a much narrower voltage regulation, which may be desirable for other reasons.

8. The division of transient reactance between two otherwise similar machines (acting as motor and generator) makes little difference, but, if the field time constants of two otherwise similar machines are different, the maximum power limit is obtained if the field of the machine with the smaller field time constant is regulated.

Analysis

PRELIMINARY REMARKS

Before entering on the detailed mathematical analysis a more or less general review of the fundamental concepts involved will be given.

For a single round-rotor synchronous machine connected to an infinite bus through a tie line or for two round-rotor machines the steady-state power transfer (with zero resistance) is given by

$$P = \frac{E_1 E_2}{x_1 + x_2} \sin \delta$$

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where E is a machine excitation or the voltage of the infinite bus, x is a machine synchronous reactance or the tie-line reactance, and δ is the angle between the two excitation axes.

It may be recognized that in the steady state (or generally, if the effects of rotor circuits are neglected) there is analytically no distinction between a tie line with its infinite bus and a second machine. The distinction lies rather in the values to be assigned to the various parameters and in the interpretation of the quantitative results.

For two equal machines or for a machine connected to a tie line of equal reactance with $x_1 = x_2 = 1.0$ and with the excitations set at some fixed value, for example, to give rated current at unity power factor and unit terminal voltage

$$E_1 = E_2 = \frac{1}{\cos 45^\circ} = 1.414$$

(see Figure 6), and the power transfer is

$$P = \frac{(1.414)^2}{2} \sin \delta = \sin \delta$$

The power limit occurs at $\delta = 90$ degrees and is $P_{\max} = 1.0$.

If, on the other hand, the excitations are not constant but are controlled so as to maintain unit voltage and power factor, then

$$E_1 = E_2 = \frac{1}{\cos \frac{\delta}{2}}$$

and the power transfer is

$$P = \frac{E_1 E_2}{x_1 + x_2} \sin \delta = \frac{\sin \delta}{2 \cos^2 \frac{\delta}{2}} = \tan \frac{\delta}{2}$$

Now the power transfer increases without limit as the angle δ is increased from 0 to 180 degrees. The new torque-angle curve crosses the old torque-angle curve at $\delta = 90$ degrees. The question of the meaning of this result, particularly of the possibility of stable operation in the region $\delta > 90$ degrees, now naturally arises; the answer is found in the kind of control used. If the excitations are controlled slowly, for example, by hand, so as to return the terminal voltage to unity only after a deviation is noticed, the power limit again will be found at $\delta = 90$ degrees. One may imagine the load increased in small steps. At each step the terminal voltage is returned to unity by an adjustment of the excitations, and then the system is tested for steady-state stability in the conventional way by noting whether or not a small increase in angle with fixed excitations results in an

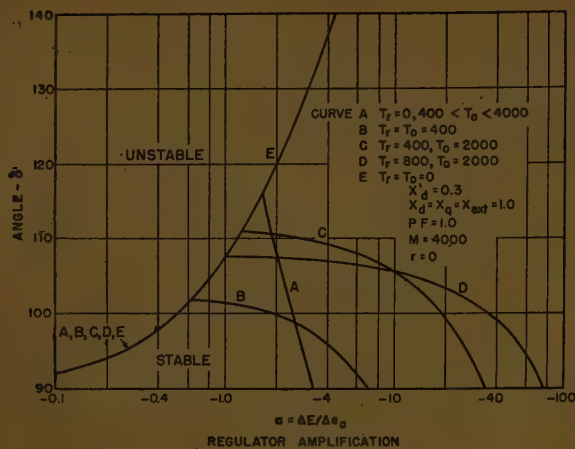


Figure 1 (left).
Effect of automatic voltage regulator on steady-state stability limit

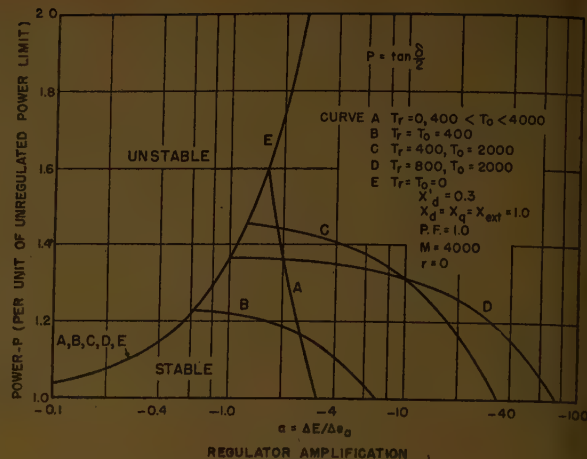


Figure 2 (right).
Effect of automatic voltage regulator on steady-state stability limit

increase or decrease in power transfer. However, if the excitations are controlled automatically to maintain constant terminal voltage continuously and instantaneously, regardless of load or angle, and even during the stability test, the relation $P = \tan \delta/2$ will hold instantaneously, and there no longer is a stability limit. In order to maintain the constant terminal voltage required for such stable operation it is necessary to have a flat regulator (that is, one with an infinite amplification factor, $a = -\infty$) and no time lags in the regulator, exciter, or even in the main machine fields, so that the excitations are corrected instantaneously. Such action is, of course, practically unrealizable because of the time lags inherent in any system. Moreover, both excitations also increase without limit as the angle δ approaches 180 degrees.

It is shown in equation 33 that, for a single machine connected to an infinite bus through a tie line of reactance $x = 1.0$, instantaneous control of only one excitation is sufficient to allow stable operation at any angle up to 180 degrees as the amplification factor is increased, but the amplification factor now must be twice as large as that required if both excitations are controlled instantaneously. Of course, the conditions of unit terminal voltage and power factor imply that, in any case, the excitations or the infinite bus voltage must be adjusted (possibly by hand) to maintain these conditions. Thus, in the limit both excitations still approach infinity as before.

If the actual case considered is really a tie line to an infinite system, rather than two machines, motor and generator of equal size, it would seem more reasonable to study the condition in which the infinite bus voltage as well as the machine terminal voltage is maintained at unity, letting the terminal power factor fall where it may. Then with a tie-line reactance and machine reactance each equal to unity, the power limit unregulated

can be shown to be $P_{\max} = 0.866$, and "ideally" regulated (to maintain unit terminal voltage instantaneously) to be $P_{\max} = 1.0$. The maximum possible improvement is seen to be very much smaller than for the two-machine case.

In order to make it easier to follow, the mathematical analysis is presented first as applied to a single machine and next, in less detail, as applied to two machines.

A. Single Machine and Tie Line. This section is concerned with the effect of a voltage regulator on the steady-state stability limit of a synchronous machine connected through an impedance tie to an infinite bus. The regulator is responsive to changes in terminal voltage or in voltage at any specified point on the tie line and acts on the field voltage of the synchronous machine. (The "regulator" of this section includes the whole regulating and excitation system.) The notation and assumptions of Park² are followed.

For the synchronous machine

$$\begin{aligned} e_a &= pG(p)E - z_a(p)i_a + [x_q(p)i_q](p\theta) \\ e_q &= G(p)E(p\theta) - x_d(p)i_a(p\theta) - z_q(p)i_q \end{aligned} \quad (1)$$

Similarly, for the tie line

$$\begin{aligned} e_a &= e \sin \delta + z(p)i_a - x_{iq}(p\theta) \\ e_q &= e \cos \delta + x_{ia}(p\theta) + z(p)i_q \end{aligned} \quad (2)$$

Δe_a	Δe_q	Δi_a	Δi_q	$\Delta \delta$	
$i_{q0}G(p)g(p)e_a'$	$i_{q0}G(p)g(p)e_q'$	$-\psi_{q0} - i_{q0}x_d(p)$	$\psi_{d0} + i_{d0}x_q(p)$	p^2M	$= \Delta T$
$pG(p)g(p)e_a' - 1$	$pG(p)g(p)e_q'$	$-z_a(p)$	$x_q(p)$	$-\psi_{q0}p$	$= 0$
$G(p)g(p)e_a'$	$G(p)g(p)e_q'$	$-x_d(p)$	$-z_q(p)$	$\psi_{d0}p$	$= 0$
-1	0	$z(p)$	$-x$	$e \cos \delta - x_{iq0}p$	$= 0$
0	-1	x	$z(p)$	$-e \sin \delta + x_{ia0}p$	$= 0$

where

$$z(p) = r + px \text{ for the tie line}$$

δ is the angle by which the machine leads the infinite bus voltage e .

Machine-torque equation

$$T = \psi_d i_q - \psi_q i_d + M p^2 \theta \quad (3)$$

where

$$M = 4\pi fH$$

From equations 1, 2, and 3 the equations for small changes from a steady-state operating position are

$$\begin{aligned} \Delta e_a &= pG(p)\Delta E - z_a(p)\Delta i_a + x_q(p)\Delta i_q - \psi_{q0}p\Delta\theta \\ \Delta e_q &= G(p)\Delta E - x_d(p)\Delta i_a - z_q(p)\Delta i_q + \psi_{d0}p\Delta\theta \\ \Delta e_a &= z(p)\Delta i_a - x\Delta i_q + (e \cos \delta - x_{iq0}p)\Delta\delta \\ \Delta e_q &= x\Delta i_a + z(p)\Delta i_q - (e \sin \delta - x_{ia0}p)\Delta\delta \\ \Delta T &= i_{q0}G(p)\Delta E - [\psi_{q0} + i_{q0}x_d(p)]\Delta i_a + [\psi_{d0} + i_{d0}x_q(p)]\Delta i_q + p^2M\Delta\theta \end{aligned} \quad (4)$$

The regulator introduces a change in field voltage E as a function of the change in magnitude of the terminal voltage e_a

$$\Delta E = g(p)\Delta e_a \quad (5)$$

where

$$e_a^2 = e_d^2 + e_q^2$$

and $g(p)$ is the operational expression for the action of the regulator

$$\begin{aligned} \Delta e_a &= e_a'\Delta e_a + e_q'\Delta e_q \\ e_a' &= e_{d0}/e_{a0} \quad e_q' = e_{q0}/e_{a0} \end{aligned} \quad (6)$$

Then

$$\Delta E = g(p)(e_a'\Delta e_a + e_q'\Delta e_q) \quad (7)$$

If equation 7 is substituted in equations 4, equations 4 become

In order to test the stability of the system, the determinant of the coefficients of equations 8 is expressed as a polynomial in p , and the signs of the real parts of the p roots are investigated by Routh's or Hurwitz's criterion.

The required initial steady-state conditions for given E , e , and δ are

$$\begin{aligned} i_{d0} &= \frac{-(r_d+r)e \sin \delta - (x+x_d)(e \cos \delta - E)}{(r_d+r)^2 + (x+x_d)(x+x_q)} \\ i_{q0} &= \frac{+(x+x_d)e \sin \delta - (r_d+r)(e \cos \delta - E)}{(r_d+r)^2 + (x+x_d)(x+x_q)} \\ \psi_{d0} &= E - x_d i_{d0} \quad e_{q0} = \psi_{d0} - r_d i_{q0} \\ \psi_{q0} &= -x_q i_{q0} \quad e_{d0} = -\psi_{q0} - r_d i_{d0} \end{aligned} \tag{9}$$

When amortisseur windings are neglected, the operational impedances are

$$\begin{aligned} x_d(p) &= \frac{x_d' T_o p + x_d}{T_o p + 1} & x_q(p) &= x_q \\ G(p) &= \frac{1}{T_o p + 1} \end{aligned} \tag{10}$$

If it is assumed that the regulator and exciter performance can be expressed as a static change (a) in field voltage E per unit change in terminal voltage e_a , together with a time lag expressible as an equivalent single time constant T_r , then

$$g(p) = \frac{a}{T_r p + 1} \tag{11}$$

Other more exact operational relations may be used in the equations, but equations 10 and 11 are the simplest and are sufficiently exact for an initial study.

If components of voltage caused by the rates of change of flux linkage and of angle are neglected, equations 8 become

Δe_d	Δe_q	Δi_d	Δi_q	$\Delta \delta$	
$i_{q0} G(p) g(p) e_d'$	$i_{q0} G(p) g(p) e_q'$	$-\psi_{q0} - i_{q0} x_d(p)$	$\psi_{d0} + i_{d0} x_q(p)$	$p^2 M$	$= \Delta T$
-1	0	$-r_d$	$x_q(p)$	0	$= 0$
$G(p) g(p) e_d'$	$G(p) g(p) e_q' - 1$	$-x_d(p)$	$-r_d$	0	$= 0$
-1	0	r	$-x$	$e \cos \delta$	$= 0$
0	-1	x	r	$-e \sin \delta$	$= 0$

(12)

If, in addition, armature and line resistance are neglected, equations 8 are reduced to

Δe_d	Δe_q	Δi_d	Δi_q	$\Delta \delta$	
$i_{q0} G(p) g(p) e_d'$	$i_{q0} G(p) g(p) e_q'$	$-\psi_{q0} - i_{q0} x_d(p)$	$\psi_{d0} + i_{d0} x_q(p)$	$p^2 M$	$= \Delta T$
-1	0	0	$x_q(p)$	0	$= 0$
$G(p) g(p) e_d'$	$G(p) g(p) e_q' - 1$	$-x_d(p)$	0	0	$= 0$
-1	0	0	$-x$	$e \cos \delta$	$= 0$
0	-1	x	0	$-e \sin \delta$	$= 0$

(13)

Equations 13 imply that the voltage equations are reduced to the form

$$\Delta e_d = -\Delta \psi_q \quad \Delta e_q = \Delta \psi_d \tag{14}$$

From equations 13 the characteristic determinant is

$$\begin{aligned} D &= i_{q0} G(p) g(p) e_d' x_q(p) x_e \cos \delta + \\ &\quad [\psi_{q0} + i_{q0} x_d(p)] [x_q(p) + x] e \sin \delta + \\ &\quad [\psi_{d0} + i_{d0} x_q(p)] [x_d(p) + x - x G(p) g(p) e_q'] e \times \\ &\quad \cos \delta + p^2 M [x_q(p) + x] [x_d(p) + x - \\ &\quad x G(p) g(p) e_q'] - \psi_{q0} [-x_q(p) + x] \times \\ &\quad G(p) g(p) e_q' e \sin \delta + \\ &\quad x_q(p) G(p) g(p) e_d' e \cos \delta \end{aligned} \tag{15}$$

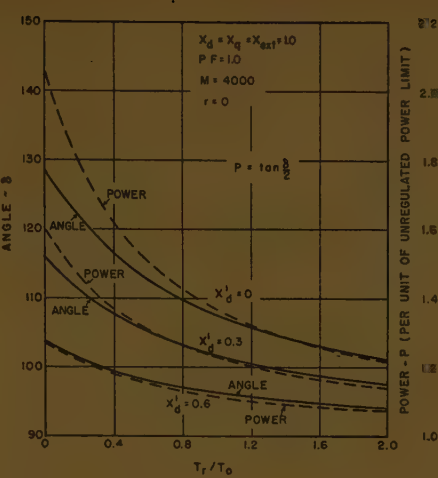


Figure 3. Effect of ratio of excitation and regulation-system time constant to field time constant on steady-state stability limit

Maximum stable operating conditions, by equation 34

For

$$x_d = x_q(p) = 1.0, (\psi_{d0} + i_{d0} x_q(p)) = E$$

B. Two Machines. The case of two synchronous machines with a voltage regulator responsive to the common bus-voltage magnitude and acting on either or both machine fields is considered in this section.

To simplify the analysis the armature resistances and the components of voltage

For machine 1

$$\begin{aligned} \Delta e_{d1} &= \omega_0 x_{q1}(p) \Delta i_{q1} \\ \Delta e_{q1} &= -\omega_0 x_{d1}(p) \Delta i_{d1} + \omega_0 G_1(p) \Delta E_1 \end{aligned} \tag{17}$$

For machine 2

$$\begin{aligned} \Delta e_{d2} &= \omega_0 x_{q2}(p) \Delta i_{q2} \\ \Delta e_{q2} &= -\omega_0 x_{d2}(p) \Delta i_{d2} + \omega_0 G_2(p) \Delta E_2 \end{aligned} \tag{18}$$

Connection of the two machines to a common bus results in the relations

$$\begin{aligned} e_{d1} &= e_{d1} \cos \delta_{12} - e_{q1} \sin \delta_{12} \\ e_{q2} &= e_{d1} \sin \delta_{12} + e_{q1} \cos \delta_{12} \\ i_{d2} &= -i_{d1} \cos \delta_{12} + i_{q1} \sin \delta_{12} \\ i_{q2} &= -i_{d1} \sin \delta_{12} - i_{q1} \cos \delta_{12} \end{aligned} \tag{19}$$

or, by differentiating

$$\begin{aligned} \Delta e_{d2} &= \Delta e_{d1} \cos \delta_{12} - \Delta e_{q1} \sin \delta_{12} - \\ &\quad (e_{d1} \sin \delta_{12} + e_{q1} \cos \delta_{12}) \Delta \delta_{12} \\ \Delta e_{q2} &= \Delta e_{d1} \sin \delta_{12} + \Delta e_{q1} \cos \delta_{12} + \\ &\quad (e_{d1} \cos \delta_{12} - e_{q1} \sin \delta_{12}) \Delta \delta_{12} \\ \Delta i_{d2} &= -\Delta i_{d1} \cos \delta_{12} + \Delta i_{q1} \sin \delta_{12} + \\ &\quad (i_{d1} \sin \delta_{12} + i_{q1} \cos \delta_{12}) \Delta \delta_{12} \\ \Delta i_{q2} &= -\Delta i_{d1} \sin \delta_{12} - \Delta i_{q1} \cos \delta_{12} - \\ &\quad (i_{d1} \cos \delta_{12} - i_{q1} \sin \delta_{12}) \Delta \delta_{12} \end{aligned} \tag{20}$$

Substituting equations 20 in equations 18, one obtains

$$\begin{aligned} \Delta e_{d1} \cos \delta_{12} - \Delta e_{q1} \sin \delta_{12} &= -\omega_0 x_{q2}(p) (\Delta i_{d1} \sin \delta_{12} + \Delta i_{q1} \cos \delta_{12}) + \\ &\quad [e_{d1} \sin \delta_{12} + e_{q1} \cos \delta_{12} - \\ &\quad \omega_0 x_{q2}(p) (i_{d1} \cos \delta_{12} - i_{q1} \sin \delta_{12})] \Delta \delta_{12} \\ \Delta e_{d1} \sin \delta_{12} + \Delta e_{q1} \cos \delta_{12} &= +\omega_0 x_{d2}(p) (\Delta i_{d1} \cos \delta_{12} - \Delta i_{q1} \sin \delta_{12}) + \\ &\quad [e_{d1} \cos \delta_{12} - e_{q1} \sin \delta_{12} + \\ &\quad \omega_0 x_{d2}(p) (i_{d1} \sin \delta_{12} + i_{q1} \cos \delta_{12})] \Delta \delta_{12} + \\ &\quad \omega_0 G_2(p) \Delta E_2 \end{aligned} \tag{21}$$

As in section A, the field voltages are given by

$$\begin{aligned} \Delta E_1 &= g_1(p) \Delta e_a = g_1(p) (e_{d1}' \Delta e_{d1} + e_{q1}' \Delta e_{q1}) \\ \Delta E_2 &= g_2(p) \Delta e_a = g_2(p) (e_{d1}' \Delta e_{d1} + e_{q1}' \Delta e_{q1}) \end{aligned} \tag{22}$$

where $g_1(p)$, $g_2(p)$ are the regulator and excitation-system characteristics for machines 1 and 2, respectively, and the torque equation of machine 1 is

$$\begin{aligned} i_{q1} G_1(p) g_1(p) (e_{d1}' \Delta e_{d1} + e_{q1}' \Delta e_{q1}) - \\ [\psi_{q1} + i_{q1} x_{d1}(p)] \Delta i_{d1} + \\ [\psi_{d1} + i_{d1} x_{q1}(p)] \Delta i_{q1} + M_1 p^2 \Delta \delta_1 = 0 \end{aligned} \tag{23}$$

Now from the voltage equations 19 and with the equations $e_d = -\omega_0 \psi_q$ and $e_q = \omega_0 \psi_d$ (by neglecting $p\psi$ and r_a), one may obtain

$$\begin{aligned} \psi_{q2} &= \psi_{q1} \cos \delta_{12} + \psi_{d1} \sin \delta_{12} \\ \psi_{d2} &= -\psi_{q1} \sin \delta_{12} + \psi_{d1} \cos \delta_{12} \end{aligned} \tag{24}$$

Thus, the flux linkage is transformed just like the voltage, and it then may be shown that

$$i_{d1} \psi_{q1} - i_{q1} \psi_{d1} = -(i_{d2} \psi_{q2} - i_{q2} \psi_{d2}) \tag{25}$$

As the electrical torques of the two machines are equal and opposite, and if there are no mechanically applied damping

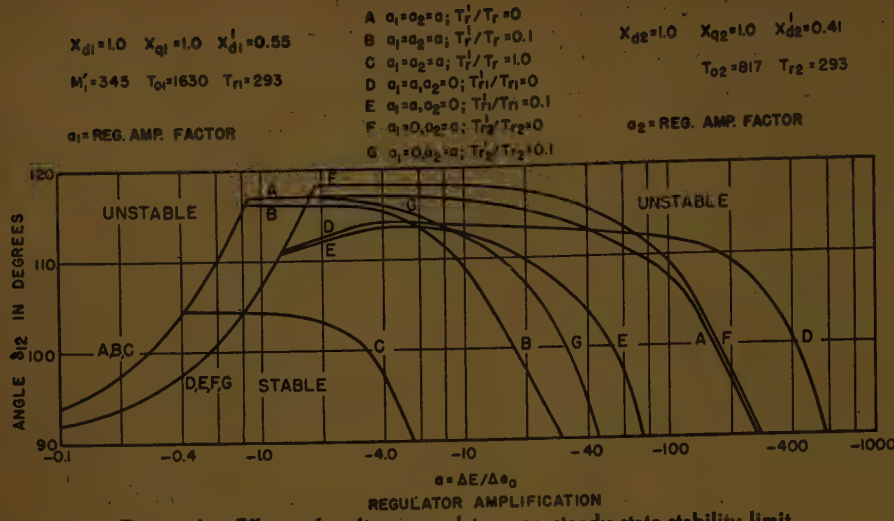


Figure 4. Effect of voltage regulators on steady-state stability limit

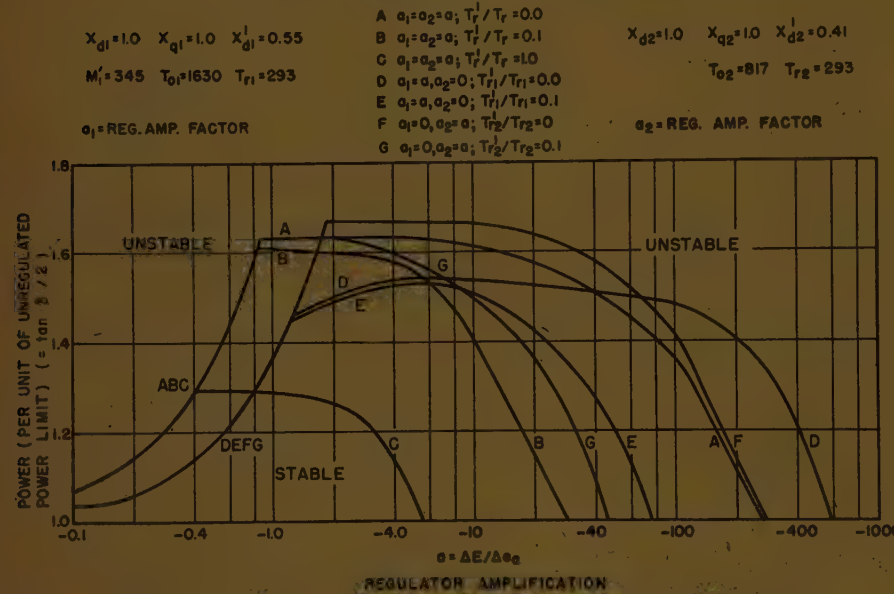


Figure 5. Effect of voltage regulators on steady-state stability limit

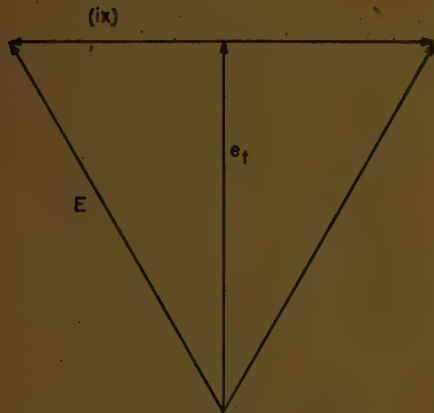


Figure 6

torques, the acceleration torques may be equated

$$M_1 p^2 \Delta \delta_1 = -M_2 p^2 \Delta \delta_2$$

$$= \frac{M_1 M_2}{M_1 + M_2} p^2 (\Delta \delta_1 - \Delta \delta_2) = M' p^2 \Delta \delta_{12} \quad (26)$$

where

$$M' = \frac{M_1 M_2}{M_1 + M_2} = \text{equivalent system inertia}$$

Thus $M' p^2 \Delta \delta_{12}$ may be substituted for $M_1 p^2 \Delta \delta_1$ in equation 23 to eliminate the extra variable $\Delta \delta_1$ and the extra torque equation. This simplification is still valid even if there are mechanical rotor damping torques, if $(D_1/M_1) = (D_2/M_2)$, in which case $(M_1 p^2 + D_1 p) \Delta \delta_1 = (M' p^2 + D' p) \Delta \delta_{12}$ where $D' = D_1 D_2 / (D_1 + D_2)$. If $(D_1/M_1) \neq (D_2/M_2)$, two torque equations are required. Considering the case of no mechanical damping, required five system equations are 23, 17, and 21, or

Δe_{d1}	Δe_{q1}	Δi_{d1}	Δi_{q1}	$\Delta \delta_{12}$	
$i_{q1} G_1(p) g_1(p) e_{d1}'$	$i_{q1} G_1(p) g_1(p) e_{q1}'$	$-\psi_{q1} - i_{q1} x_{d1}(p)$	$\psi_{d1} + i_{d1} x_{q1}(p)$	$M' p^2$	$= 0$
-1	0	0	$\omega_0 x_{q1}(p)$	0	$= 0$
$\omega_0 G_1(p) g_1(p) e_{d1}'$	$\omega_0 G_1(p) g_1(p) e_{q1}' - 1$	$-\omega_0 x_{d1}(p)$	0	0	$= 0$
$\cos \delta_{12}$	$-\sin \delta_{12}$	$\omega_0 x_{q2}(p) \sin \delta_{12}$	$\omega_0 x_{q2}(p) \cos \delta_{12}$	$-e_{q2} - \omega_0 x_{q2}(p) i_{d2}$	$= 0$
$\sin \delta - \omega_0 G_2(p) g_2(p) e_{d1}'$	$\cos \delta - \omega_0 G_2(p) g_2(p) e_{q1}'$	$-\omega_0 x_{d2}(p) \cos \delta_{12}$	$\omega_0 x_{d2}(p) \sin \delta_{12}$	$e_{d2} - \omega_0 x_{d2}(p) i_{q2}$	$= 0$

(27)

The determinant of the coefficients of equations 11 is

$$M' p^2 \{ x_{d1} x_{q1} + x_{d2} x_{q2} + (x_{d1} x_{q2} + x_{d2} x_{q1}) \times \cos^2 \delta + (x_{d1} x_{d2} + x_{q1} x_{q2}) \sin^2 \delta - G_1 G_1 \times [x_{q1} (x_{d2} - x_{q2}) e_{d1}' \sin \delta \cos \delta + e_{q1}' (x_{d2} x_{q2} + x_{d2} x_{q1} \cos^2 \delta + x_{q1} x_{q2} \sin^2 \delta)] - G_2 g_2 [x_{q1} (x_{d1} + x_{q2}) e_{d1}' \sin \delta + x_{d1} \times (x_{q1} + x_{q2}) e_{q1}' \cos \delta] + (\psi_{d1} + i_{d1} x_{q1}) \times \{ (e_{d2} - x_{d2} i_{q2}) [(G_1 g_1 e_{q1}' - 1) x_{q2} - x_{d1}] \times \sin \delta - (e_{q2} + x_{q2} i_{d2}) [(G_1 g_1 e_{q1}' - 1) x_{d2} - x_{d1}] \times \cos \delta + x_{d1} G_2 g_2 e_{q1}' \} + (\psi_{q1} + i_{q1} x_{d1}) \times (G_2 g_2 e_{d1}' x_{q1}) (e_{q2} + x_{q2} i_{d2}) + G_1 g_1 e_{q1}' x_{q1} \times \{ (e_{d2} - x_{d2} i_{q2}) (\psi_{q1} - i_{q1} x_{q2}) \sin \delta - (e_{q2} + x_{q2} i_{d2}) (\psi_{q1} - i_{q1} x_{d2}) \cos \delta \} + [\psi_{q1} (G_1 g_1 e_{q1}' - 1) - i_{q1} x_{d1}] [(e_{d2} - x_{d2} i_{q2}) \times (x_{q1} + x_{q2}) \cos \delta + (e_{q2} + x_{q2} i_{d2}) \times (x_{q1} + x_{d2}) \sin \delta] \} \quad (28)$$

where in equation 28 $G_1(p)$, $x_{d1}(p)$, and so forth have been written for convenience as G_1 , x_{d1} , and so forth; ω_0 has been taken as 1.0; and δ_{12} has been written simply as δ .

For the special case $x_{d1}(0) = x_{d2}(0) = x_{q1}(p) = x_{q2}(p) = e_a$ = power factor = 1.0 (two round-rotor machines with equal steady-state reactances and equal excitations) the determinant 28 reduces to

$$2 \cos^2 \frac{\delta}{2} M' p^2 \{ [x_{d1}(p) + x_{d2}(p)] \times (1 + \cos^2 \delta) + [1 + x_{d1}(p) x_{d2}(p)] \sin^2 \delta - [G_1(p) g_1(p) + G_2(p) g_2(p)] \sin \delta \sin \frac{\delta}{2} - 2 [G_1(p) g_1(p) x_{d2}(p) + G_2(p) g_2(p) x_{d1}(p)] \cos^2 \frac{\delta}{2} \} + [(2 - \cos \delta) - (2 + \cos \delta) \times x_{d1}(p) x_{d2}(p)] \sin^2 \delta + [x_{d1}(p) + x_{d2}(p)] (2 + \sin^2 \delta) \cos \delta - [G_1(p) g_1(p) + G_2(p) g_2(p)] \sin \delta \sin \frac{\delta}{2} - 2 [G_1(p) g_1(p) x_{d2}(p) + G_2(p) g_2(p) x_{d1}(p)] \cos^2 \frac{\delta}{2} \quad (29)$$

Application

A. SINGLE MACHINE AND TIE LINE

Equation 15 (or the similar equations derivable from equations 12 or 8) can be used to determine the stability limits of the single machine system over a range of circuit constants. The quantities which can be varied are:

1. Regulator amplification factor a .
2. Machine field time constant T_0 .
3. Regulator and exciter time constant T_r (for the simple case of equation 11).

4. External reactance x .
5. Terminal power factor.
6. Transient reactance x_d' .
7. Moment of inertia M .
8. Location of regulator (that is, at machine terminals or along tie line).
9. Quadrature axis reactance x_q .
10. External resistance r .
11. Amortisseur characteristics.
12. More complex regulating systems, including stabilizers.

A study of the effects of the first three of these quantities has been made with the remaining quantities fixed at the values

$$\begin{aligned} x &= x_q = x_d = 1.0 \\ \text{Power factor} &= 1.0 \\ x_d' &= 0.3 \\ M &= 4,000 \text{ (or } H = 5.3) \\ \text{Simple regulator at machine terminals} \\ r &= 0 \\ \text{No amortisseur} \end{aligned} \quad (30)$$

Under these conditions the maximum operating angle with no regulator is $\delta = 90$ degrees, and with unit terminal voltage ($e_a = 1.0$) the machine field and infinite bus voltages are $E = e = (\cos \delta / 2)^{-1}$. Also, from equations 9

$$\begin{aligned} \frac{\sin^2 \frac{\delta}{2}}{\cos \frac{\delta}{2}} \quad \psi_{qo} &= -i_{qo} = -\sin \frac{\delta}{2} \\ e_{do}' &= e_{do} = -\psi_{qo} = \sin \frac{\delta}{2} \\ i_{qo} &= \sin \frac{\delta}{2} \\ \psi_{do} &= \cos \frac{\delta}{2} \quad e_{qo}' = e_{qo} = \psi_{do} = \cos \frac{\delta}{2} \end{aligned} \quad (31)$$

From equations 10

$$\begin{aligned} x_d(p) &= \frac{0.3T_o p + 1}{T_o p + 1} \\ x_q(p) &= 1 \\ G(p) &= \frac{1}{T_o p + 1} \end{aligned}$$

If some of these relations are substituted in equation 15, it becomes

$$\begin{aligned} &+ p^4 M [T_o T_r (1 + x_d')] \cos^2 \frac{\delta}{2} \\ &+ p^4 M [T_o (1 + x_d') + 2T_r] \cos^2 \frac{\delta}{2} \\ &+ p^2 \left\{ 4M \left(2 - a \cos \frac{\delta}{2} \right) \cos^2 \frac{\delta}{2} + \right. \\ &\quad \left. 2T_r T_o [(1 + x_d') \cos \delta + (1 - x_d') \sin^2 \delta] \right\} \\ &+ p [2T_o [(1 + x_d') \cos \delta + (1 - x_d') \sin^2 \delta] + \\ &\quad 4T_r \cos \delta] \\ &+ \left(4 \cos \delta - 2a \cos \frac{\delta}{2} \right) \end{aligned} \quad (32)$$

Equation 32 is in a form such that, in addition to the quantities studied, the rotor-inertia M and transient-reactance x_d' can be varied also.

Results for Single Machine. Figures 1 and 2 show some of the results obtained. Figure 1 shows the maximum permissible operating angles between the machine and the bus, and Figure 2 shows the corresponding power limits as functions of the amplification factor a of the regulating system. Curve E , for no time lags in either the regulator or machine field, that is, for $T_r = T_o = 0$, is seen from

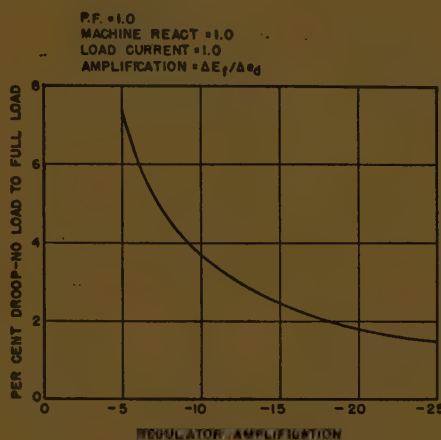


Figure 7. Relation between regulator amplification and voltage droop

equation 32 to be given by the simple formula:

$$a = \frac{2 \cos \frac{\delta}{2}}{\cos \frac{\delta}{2}} \quad (33)$$

The maximum stable operating angle is $\delta = 180$ degrees (90 degrees between the machine direct axis and its terminals and 90 degrees between the machine terminals and the bus voltage) for $a = -\infty$, with a corresponding infinite power (see section, "Preliminary Remarks").

If $T_o \neq 0$ (with $T_r = 0$ still) the possible increase in power limit is at once very much reduced, and an upper limit of $(-a)$ is found (see curve A). It may be shown that, for all of the curves of Figures 1 and 2, the maximum stable operating angle occurs when the coefficients of p^1 and p^0 in equation 3 are simultaneously equal to zero. For these cases the maximum possible stable operating angle is given by the formula

$$\cos \delta = b - \sqrt{b^2 + 1} \quad (34)$$

where

$$b = \frac{(1 + x_d' + 2 \frac{T_r}{T_o})}{2(1 - x_d')}$$

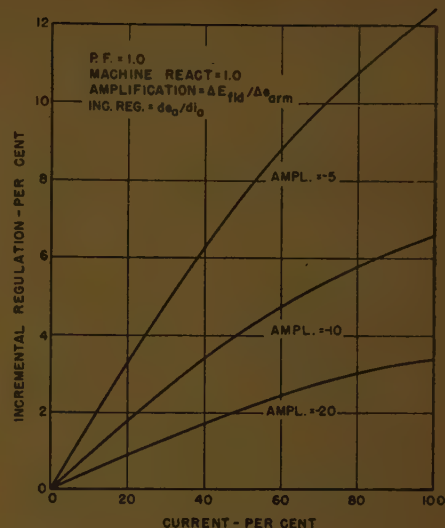


Figure 8. Relation between incremental regulation and regulator amplification

Figure 3 shows a plot of equation 34. This equation has been verified only in the range studied and should not be used over a much wider range without further check calculations by equation 32. The required values of regulator amplification factor a corresponding to the conditions of Figure 3 may be found from equation 33.

If $T_r/T_o = 0$, the maximum possible stable operating angle is that corresponding to $T_o = \infty$. This may be seen by comparing equation 34 to the case $T_o = \infty$, $T_r = 0$ in equation 32. Setting $T_o = \infty$ is equivalent to maintaining constant field flux linkages, in which case the steady-state power limit may be calculated by replacing the direct-axis synchronous reactance by the direct-axis transient reactance in the salient-pole synchronous-machine power-transfer formula, and the regulator action need not be considered. (Similarly, in the case of two regulated machines, the direct-axis reactances of both machines may be replaced in the limit by the direct-axis transient reactances.) Note that the power limits so obtained may be considerably different from those which would be found by replacing both x_d and x_q by x_d' .

Curves B , C , and D of Figures 1 and 2 show the further reduction caused by the introduction of a time lag in the regulation and excitation systems. Although a time lag decreases the maximum attainable angle and power limit, it allows operation over a considerably greater range in regulator amplification factor a .

If $T_o = 0$ but $T_r > 0$, no improvement in stability is possible. To the contrary, any attempt to control the field voltage reduces the stability limit. This is evident from equation 32. The detrimental

effect of a high ratio of T_r/T_o is also evident from Figure 3.

B. RESULTS FOR TWO MACHINES

1. *Location of Regulated Excitation.* It is not necessary that the field of each machine be controlled by the same amount. If there is any advantage in so doing, the relative amounts of field-excitation change produced on the two machines for a given voltage change may be made anything within reason. Therefore, calculations were made (by equation 29) to determine what the optimum arrangement should be. For this purpose the regulator and excitation-system characteristics were represented by

$$g(p) = \frac{a}{T_r p + 1} = \frac{a}{293p + 1} \quad (35)$$

This is the simplest possible characteristic; the exciter is assumed to have a 293-radian time constant, and all other lags in the regulating system are neglected.

Three arrangements were studied:

a. Regulation only on machine 1

$$g_1(p) = \frac{a}{293p + 1} \quad g_2(p) = 0 \quad (36a)$$

b. Regulation equal on both machines

$$g_1(p) = g_2(p) = \frac{a}{293p + 1} \quad (36b)$$

c. Regulation only on machine 2

$$g_1(p) = 0 \quad g_2(p) = \frac{a}{293p + 1} \quad (36c)$$

Figures 4 and 5, curves A, D, and F, show the results and indicate that there is little difference among the three arrangements, so that the amount of stability gain is not critical to the relative field-excitation characteristics. The values of optimum amplification factor are smaller if the voltage regulation is equal on both machines, but this is only what should be expected, since the total required

changes of field current on both machines tend to remain constant.

Comparison of Figures 4 and 5 with 1 and 2 shows also that the possible gain with two more or less similar machines is greater than for one machine and tie line. This appears to be a reasonable result when it is recalled that the lower the transient reactance the more the gain, and that the total transient reactance of two machines is, of course, smaller than that of one machine and a tie line.

2. *Additional Lags in Regulating System.* Since an actual regulating system may be made up of several stages, each having some time lag, the next step is to find out how important these lags are. The three regulator arrangements discussed in section 1 were, therefore, recalculated with the regulating system represented by the expression

$$g(p) = \frac{a}{(T_r p + 1)(T_r' p + 1)} = \frac{a}{(293p + 1)(29.3p + 1)} \quad (37)$$

This allows for a lag of $T_r' = 29.3$ radians in the regulator in addition to the lag of $T_r = 293$ radians in the exciter. The amount of possible gain in stability is seen by curves B, E, and G of Figures 4 and 5 to be somewhat smaller. Also, the permissible range of regulation or of amplification factor a is restricted still further. Although the reduction in gain is not alarming, it is sufficient to indicate that every effort should be made to reduce regulator lag.

Figures 4 and 5 also show curves C for the case of equal regulating effort on both machines with a 293-radian time lag T_r' in the regulator

$$g(p) = \frac{a}{(293p + 1)^2} \quad (38)$$

The possible gain and allowable range of regulation are reduced greatly by this

larger additional lag, as in the case of one machine.

Appendix. Relation Between Regulator and Excitation-System Amplification and Voltage Regulation

Figures 7 and 8 have been computed to show what the amplification factor (a) discussed in this paper means in terms of voltage regulation of the system. The vector diagram is as shown in Figure 6 for two equal round-rotor machines. From the diagram

$$e_i^2 + (ix)^2 = E^2 \quad (39)$$

For the regulated excitation system

$$E = E_o - a(e_{io} - e_i) \quad (40)$$

whence the equation for e_i is

$$(a^2 - 1)e_i^2 + 2a(E_o - ae_{io})e_i + (E_o - ae_{io})^2 - (ix)^2 = 0 \quad (41)$$

with

$$E_o = e_{io} = ix = 1.0$$

$$(a^2 - 1)e_i^2 + 2a(1 - a)e_i + (1 - a)^2 - 1 = 0 \quad (42)$$

Equation 42 allows one to calculate the voltage droop from no load ($i=0$) to full load ($ix=1$) for any amplification factor a . Results are shown in Figure 7.

Also, from equations 39 and 40 one obtains for the incremental regulation, defined as de_i/di , the relation

$$\frac{de_i}{di} = -\frac{x^2 i_o}{(e_{io} - E_o a)} \quad (43)$$

Results are shown in Figure 8.

The conclusions for this unity terminal power-factor case are that the over-all droop is about 40 per cent of the negative of the reciprocal of the amplification factor, and the incremental regulation increases from zero with increasing initial load, being equal to the over-all droop at about half load.

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A New Differential Analyzer

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Synopsis: This paper describes a new 14-integrator differential analyzer recently placed in service by the General Electric Company at Schenectady. This analyzer has a mechanical interconnection system but has integrators of novel design in that a Polaroid follow-up system is used rather than the more usual mechanical torque amplifiers.

TECHNICAL progress creates a need for tools which are capable of analyzing physical phenomena more accurately and rapidly. Electric calculating devices (d-c calculating boards, a-c network analyzers, and transient analyzers) represent significant attainments in fulfilling this growing need.

The development of the differential analyzer, both in this country and abroad, has kept a timely pace with technical progress. Early contributions to this development led to the construction of such an analyzer at the Massachusetts Institute of Technology.¹ Since that time several other similar analyzers have been constructed.^{4,5,6,9,10,12,13} The value of such a device as a precision tool for the purpose of solving ordinary differential equations has been well established. Since 1935 General Electric Company engineers have used the University of Pennsylvania differential analyzer for the solution of many important problems. Most of the studies were made jointly with members of the Moore School staff, and some were of sufficient general interest to result in published articles.

With this experience and the increasingly important part played by the other various types of analyzers in carrying on analytical engineering work, the General Electric Company has built and recently put into operation at Schenectady a new differential analyzer. It is the purpose of this paper to describe this analyzer.

Fundamental Principles

The differential analyzer is fundamentally a device for the automatic solution of differential equations. One of the most

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important component parts of such a device is the means for accomplishing integration. While several known devices may serve as integrators, one which has served this purpose well over a number of years is the Kelvin wheel-and-disk type. This device is best described functionally by referring to Figure 1. In this figure the angular rotation of the turntable or disk, α , is proportional to the independent variable. The point of contact between the integrator wheel of radius R and this disk is restricted to a straight-line parallel to the axis of rotation of the wheel and passing through the center of the turntable. Its radial position from the center of this disk is defined as r . If there is no slip between the wheel and disk, then at any instant the arc $r d\alpha$ is equal to the arc $R d\beta$, and, therefore

$$d\beta = \frac{r}{R} d\alpha$$

Consequently

$$\beta = \frac{1}{R} \int_{\alpha_1}^{\alpha_2} r d\alpha$$

and it follows that the angular rotation of the integrator wheel is the integral of the variable radius r with respect to the angular rotation α of the turntable between the limits, as defined by α_1 and α_2 with proper regard for signs and mechanical constants of the device. In such a device the radius r may be controlled by the rotation of a lead screw. Thus, integration can be accomplished in terms of the angular rotation of three shafts, namely, the turntable drive shaft, the lead-screw shaft, and the integrator-wheel shaft, the last always being the integral of the angular rotation of the lead-screw shaft with

respect to the angular rotation of the turntable drive shaft.

Although these are the essential parts of an integrating device of this type, one additional element is most important in making it a practical device. In the solution of differential equations it is invariably necessary for the rotation of the integrator wheel to produce sufficient torque to drive the output shaft. The lightweight integrator wheel in contact with the turntable is not capable of producing this required torque. Some means of translating the angular position of the integrator wheel to another shaft through a means capable of supplying the required torque is necessary. The newly developed Polaroid follow-up system used to accomplish this purpose in the new General Electric differential analyzer will be described later in this paper.

The basic elements of a complete differential analyzer are shown in Figure 2. In this figure an input table, an output table, and an integrator are shown connected together with a motor which provides angular rotation proportional to the independent variable. As this motor rotates the integrator turntable rotates, and, simultaneously, the input- and output-table horizontal lead screws rotate, causing the carriage supporting the vertical lead-screw assemblies to move toward the right on both input and output tables. If, as this motion takes place, the crank on the splined shaft of the input table is rotated so as to keep a pointer on the curve drawn, and if this cranked angular rotation is made to drive the lead screw of the integrator, then the angular-rotation β of the integrator wheel is the integral of the function being followed on the input table with respect to the angular-rotation α of the motor drive, which is the independent variable. The angular-rotation β of the integrator wheel is transmitted through a follow-up system to the vertical lead-screw drive of the output table. Thus, the pencil supported by the output-

Table 1. Integrator-Wheel Slip Measurements

Integrator Lead-Screw Setting	Integrator- Wheel Rpm	Equivalent Revolutions		Per Cent Difference	Output Torque (Pound-Inches)
		Integrator Wheel	Turntable		
-64.00.....	1,000.....	1,006.00.....	1,006.30.....	+0.030.....	0
-64.00.....	480.....	1,000.52.....	1,000.99.....	+0.047.....	0
-64.00.....	240.....	993.15.....	993.50.....	+0.035.....	0
-48.00.....	480.....	1,003.20.....	1,003.35.....	+0.015.....	0
-32.00.....	480.....	1,009.72.....	1,009.89.....	+0.017.....	0
-16.00.....	480.....	1,004.81.....	1,005.07.....	+0.026.....	0
+64.00.....	480.....	994.81.....	994.93.....	+0.008.....	0
+48.00.....	480.....	992.53.....	992.45.....	-0.008.....	0
+32.00.....	480.....	1,000.21.....	1,000.33.....	+0.012.....	0
+16.00.....	480.....	1,001.04.....	1,000.35.....	-0.069.....	0
+64.00.....	1,000.....	998.56.....	998.49.....	-0.007.....	5.0
+64.00.....	1,000.....	996.26.....	996.19.....	-0.007.....	6.0
+64.00.....	1,000.....	996.04.....	995.99.....	-0.005.....	9.0

table carriage traces a curve which is the integral of the curve $r = K\alpha$ on the input table, with respect to the independent variable α , appropriate regard being given to constants and boundary conditions.

It is not always necessary to crank in functions, for, in many cases, they can be generated. In the example shown, for instance, the function $r = K\alpha$ being integrated is proportional to the independent variable α and, consequently, could be obtained directly from the motor drive with suitable gear ratios. However, this example was used as an elementary illustration of the function of the fundamental component parts of a differential analyzer. In general, input tables are used to crank in experimental functions which cannot be expressed conveniently analytically, but which, nevertheless, are known.

Design Considerations

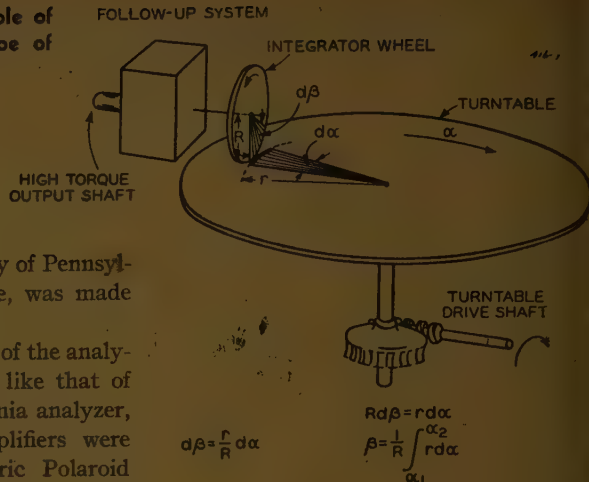
Experience with the differential analyzer of the Moore School at the University of Pennsylvania in Philadelphia served as a basis for establishing certain criteria of performance which were desired in such a device to best meet the particular needs. Among the desired objectives were:

1. Flexibility.
2. Speed of solution.
3. Accuracy.
4. Low maintenance.
5. Reasonable time and cost required for construction.

While successful and satisfactory means for solving differential equations need not be patterned after existing analyzers, and it is realized that other means may offer excellent possibilities, these possibilities could be realized only after an extended development program. On the other hand, the use of an analyzer as a tool for the solution of design and system problems was desired at the earliest possible date. This fact played an important part in the formulation of the plans for building such a device.

Experience with the mechanical interconnection system at the University of Pennsylvania, which is similar to that employed in the analyzer described by Vannevar Bush, indicated that this system has a high degree of flexibility that is very desirable in a device to be used for the solution of many different types of problems. Such a system has proved satisfactory over a number of years of relatively continuous operation in several analyzers. With the wholehearted co-operation of the University of Pennsylvania, drawings, patterns, and so forth, already completed for this part of the analyzer were made available. Professor

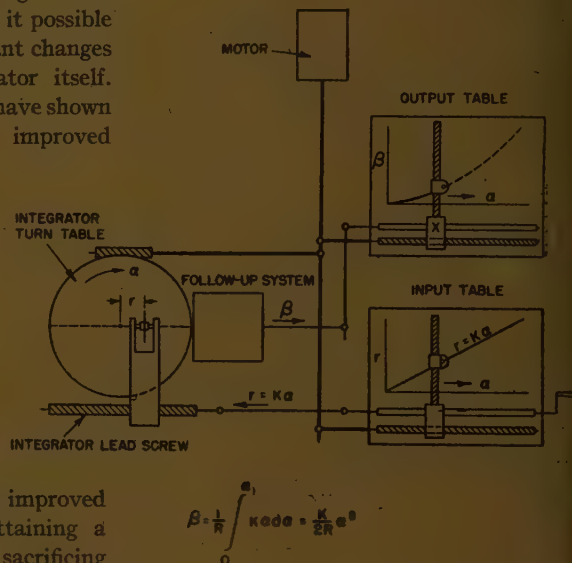
Figure 1. Fundamental principle of the Kelvin, wheel-and-disk type of mechanical integrator



Irven Travis of the University of Pennsylvania, now in active service, was made available as consultant.

While the mechanical part of the analyzer was constructed mainly like that of the University of Pennsylvania analyzer, the mechanical torque amplifiers were replaced by General Electric Polaroid follow-up systems of novel design. The use of these new devices made it possible to make desirable and significant changes in the design of the integrator itself. Tests on these new integrators have shown that they contribute toward improved

Figure 2. Schematic representation of the interconnections of the basic differential-analyzer elements

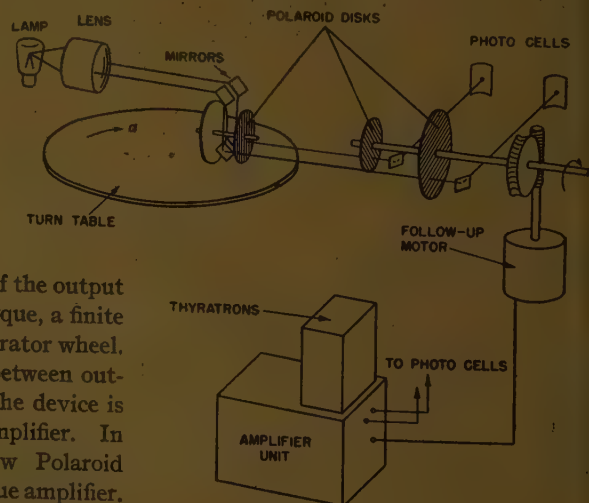


analyzer performance. This improved performance is realized in attaining a shorter solution time without sacrificing the desired degree of accuracy. Also, since adjustments once made need not be made periodically, as is the case with the conventional mechanical analyzer, time lost through maintenance is kept at a minimum.

The Polaroid Follow-up System

Mechanical torque amplifiers, as used on existing analyzers, require that, in

Figure 3. Schematic representation of the Polaroid follow-up system



order to change the position of the output shaft and produce driving torque, a finite torque be applied to the integrator wheel. Thus, there is a finite ratio between output and input torques, and the device is correctly named a torque amplifier. In contrast with this, the new Polaroid follow-up system is not a torque amplifier.

system^{11,14} can be explained best by referring to Figure 3. On the shaft of the integrator wheel, which is in contact with the turntable, is rigidly mounted a Polaroid disk. This shaft turns on jeweled bearings as the turntable is rotated. Light from a lamp source is brought through a condensing lens and infrared eliminating filter system. The infrared filter is necessary in order to eliminate that portion of the spectrum which is least polarized by the Polaroid system. Light from the condensing lens is directed to a set of mirrors supported rigidly on the integrator-wheel carriage. These mirrors reflect the incoming horizontal light vertically downward as two separate parallel beams. These beams in turn are intercepted by a second set of mirrors directly below, which reflect the incoming light as two horizontal beams which pass through the Polaroid disk. This Polaroid disk polarizes the two beams of light in the direction of the axis of polarization indicated by the parallel lines shown. These two parallel beams of polarized light continue and pass through separate Polaroid disks on the output shaft. One of these Polaroid disks is made larger than the other, and the axes of the integrator wheel and output shaft are displaced in parallel relation in order to make this separation of light beams possible. The two output-shaft Polaroid disks have their axes of polarization displaced by 90 degrees with respect to each other. Each beam, as it comes through its respective Polaroid disk, is again reflected horizontally at right angles to the incident beam. Each of these two beams falls upon a photocell.

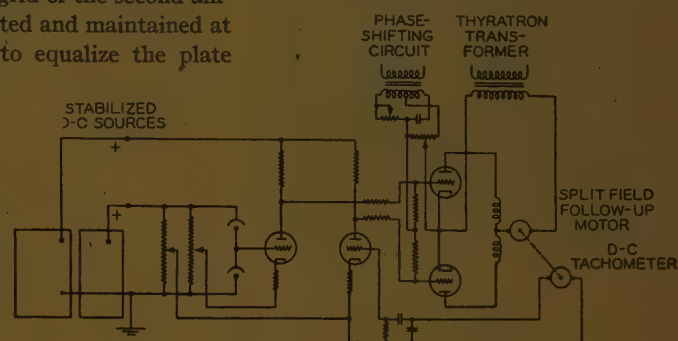
If the axis of polarization of the Polaroid disk on the integrator-wheel shaft lies intermediate between the two axes of polarization of the Polaroids on the output shaft, then the light intensity is the same on both photocells. If the integrator wheel becomes slightly displaced from this intermediate position of balanced light, then one photocell receives more and the other less light. The direction of this displacement determines which of the two photocells receives more light, and, consequently, which receives less.

The two photocells form two branches of a bridge circuit which is balanced when the axis of the Polaroid disk on the integrator wheel shaft is intermediate between the axes of polarization of the two Polaroid disks on the output shaft. Any unbalance between the two light beams falling on the photocells causes a corresponding directional unbalance in this bridge circuit, which in turn is amplified, so as to control the firing of thyatron tubes. The

controlled current through these tubes flows through a split-field series follow-up motor, causing it to turn in the direction required to maintain the balance of the photocell bridge circuit.

The basic circuit required to translate the photocell signal to the motor driving the output shaft is shown schematically in Figure 4. It is seen that the photocells are connected in series, and the midpoint is connected to the grid of one of the amplifier tubes. The grid of the second amplifier tube is adjusted and maintained at a potential so as to equalize the plate

Figure 4. Schematic circuit diagram of the photocell amplifier and thyatron follow-up motor drive



voltages on the two amplifier tubes when the two photocells receive an equal amount of light corresponding to balance. Thus, under balanced light conditions, the voltage from plate to plate of the amplifier tubes is zero. A displacement of the integrator wheel in one direction, with the output shaft stationary, causes a d-c voltage to appear between these two plates. If the direction of displacement is reversed, the polarity of this d-c voltage is reversed. The desired directional signal is thus available between the plates of the two amplifier tubes. This signal in turn is brought to the grids of the two thyatron tubes, making one grid positive with

respect to the other for a displacement of the integrator wheel in one direction, and one grid negative with respect to the other one for a displacement in the opposite direction. Thus, with one thyatron in each half of the split-field winding, and with alternating current applied to the thyratrons, field and armature in series as shown in Figure 4, a displacement of the integrator wheel with respect to the output shaft causes one or the other thya-

tron to conduct; the one conducting depending on the direction of this displacement.

It is desirable under balanced conditions that these two thyratrons conduct a small current equal in the two tubes for high sensitivity, thus producing no average motor torque. Also, the motor torque should increase rapidly and smoothly with angular displacement of the integrator wheel from the position of balance. In order to accomplish this, an a-c voltage adjustable in amplitude and phase with respect to the alternating current applied to the motor is introduced, as shown in Figure 4. When this a-c grid voltage

Table II. Typical Sine-Wave Growth Measurements

Maximum Integrator-Wheel Speed	Amplitude (Revolutions of Lead Screw)	Average Growth Per Cycle (Revolutions)	Per Cent Growth Per Cycle	Step Down	Gears for Train
970.....	50.00.....	0.525.....	1.05.....	None.....	None.....
780.....	40.00.....	0.400.....	1.00.....	None.....	None.....
390.....	20.00.....	0.194.....	0.97.....	None.....	None.....
510.....	60.00.....	0.225.....	0.375.....	None.....	None.....
335.....	40.00.....	0.175.....	0.437.....	None.....	None.....
170.....	20.00.....	0.135.....	0.675.....	None.....	None.....
262.....	60.00.....	0.135.....	0.225.....	None.....	None.....
175.....	40.00.....	0.128.....	0.320.....	None.....	None.....
87.....	20.00.....	0.104.....	0.520.....	None.....	None.....
200.....	64.00.....	0.129.....	0.202.....	1:4.....	1 pair.....
200.....	32.00.....	0.130.....	0.406.....	1:4.....	1 pair.....
200.....	16.00.....	0.123.....	0.770.....	1:4.....	1 pair.....
600.....	64.00.....	0.158.....	0.247.....	1:4.....	1 pair.....
1,000.....	64.00.....	0.174.....	0.272.....	1:4.....	1 pair.....
600.....	32.00.....	0.147.....	0.459.....	1:4.....	1 pair.....
1,000.....	32.00.....	0.162.....	0.506.....	1:4.....	1 pair.....
200.....	64.00.....	0.090.....	0.141.....	1:16.....	2 pairs.....
200.....	32.00.....	0.091.....	0.284.....	1:16.....	2 pairs.....
200.....	16.00.....	0.084.....	0.525.....	1:16.....	2 pairs.....
600.....	64.00.....	0.103.....	0.161.....	1:16.....	2 pairs.....
1,000.....	64.00.....	0.100.....	0.156.....	1:16.....	2 pairs.....
600.....	32.00.....	0.091.....	0.284.....	1:16.....	2 pairs.....
1,000.....	32.00.....	0.096.....	0.300.....	1:16.....	2 pairs.....



Figure 5. Integrator output-shaft motor drive showing the worm and compound gear and the optical arrangement of the Polaroid disks and mirrors

In back of the motor drive is shown the magnetic-clutch arrangement in the integrator lead-screw shaft



Figure 6. Top view of integrator unit showing the details of the carriage assembly and of the carriage drive

lags the a-c motor voltage by approximately 90 degrees, the d-c voltage from the amplifier causes firing of the thyratrons over increasing portions of the positive half of the a-c motor voltage wave, the portion being continuously increased over the entire positive half cycle depending upon the magnitude of the d-c signal from the amplifier. Thus, the sensitivity is determined mainly by the d-c volts output per degree of angular displacement of the integrator wheel with respect to the

Figure 7. Top view of one of the double integrator-unit assemblies

The steel cabinet underneath the integrator table contains the thyatron transformer, auxiliary transformers, time-delay relay for the thyatron plate circuits, and various switches



balance point corresponding to equal illumination on the two photocells.

It is well known that, in sensitive follow-up systems such as this, stability is one of the most difficult problems. In particular, where the conditions of operation, as to speed, load, acceleration, inertia, and reversing, range over the extremes which are necessarily encountered in operating a flexible device such as this one, it attains most difficult proportions. Some effective means of stabilization is essential to satisfactory performance. One means of attaining stability is illustrated in Figure 4. The d-c tachometer shown is mounted on the same shaft as the d-c motor armature. It furnishes an output voltage proportional to speed which is used as an indication of output-shaft speed, and also through a resistance-capacitance network gives a signal across a resistance which has a component proportional to rate of change of speed. This signal is applied to the grid of the second amplifier tube as shown. In the case of a quick displacement of the integrator wheel requiring high acceleration of the motor, this signal partially counteracts the signal due to the photocell light unbalance, thus causing the output shaft to approach the position of balance more gradually than would be possible otherwise. Hence, with proper adjustment, the tendency to overshoot is diminished, and sustained oscillations or "hunting" cannot exist. This system of stabilization has been used with good results.

When several integrators are cascaded, the general stability problem becomes

more difficult. Substantial progress toward the goal of further improved stability under these conditions has been made.

Figure 5 illustrates the output-shaft motor drive with cover removed. This shows the two output-shaft Polaroid disks and mirrors which reflect the two polarized light beams on the photocells. It also shows the follow-up motor mounting and the worm-gear drive. The worm gear is made of a special compound to withstand mechanical wear. Figure 6 is a top view of the integrator showing the carriage supporting the integrator wheel, Polaroid disk, mirror assembly, and the glass turntable.

The Integrators

The integrators fundamentally are of the Kelvin disk-and-wheel type, as illustrated in Figure 1. A top view of two associated integrator units is shown in Figure 7. In the design of the complete integrator every effort was made to take advantage of the light-beam system of transmission to obtain a freely running, stable, precision unit.

Since there is no mechanical connection between the integrator-wheel shaft and the output shaft, it is possible to move the integrator-wheel assembly in its carriage parallel to the lead screw rather than to move the entire turntable with respect to the integrator-wheel assembly. Thus, the axis of rotation of the turntable remains fixed in position, and the turntable is rotated by means of a simple right-angle

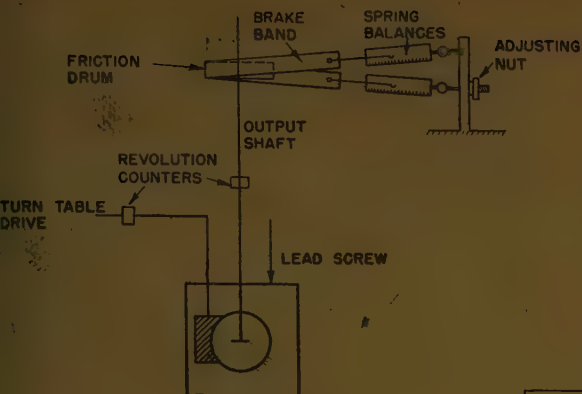


Figure 8. Mechanical integrator connections for slippage performance tests of Table I

The integrator output torque is adjusted by means of friction drum, brake band, and spring balances. Without slippage the revolution counters in the turntable drive and output shaft show a constant relationship

drive, no splined shafts being necessary. The lead screw for the integrator-wheel carriage is parallel to the directed light beams, so that, for any setting of the lead screw in the proper range of carriage travel, the light beams always will be directed properly through the optical system.

The integrator-wheel assembly is mounted in a pivoted support which permits free vertical movement of the wheel, thus assuring that it will remain in contact with the plate-glass disk. The wheel is of stainless steel, two inches in diameter, with a rim having a $\frac{1}{32}$ -inch radius of curvature. Only a light pressure is required between the wheel and turntable, because, regardless of output-shaft load, all that is needed is sufficient friction force to turn the light integrator-wheel-shaft assembly in its jeweled bearings. The carriage is, thus, merely a guide for the almost frictionless balanced integrator wheel. Statics, there is very little pressure on the jeweled bearing surfaces; dynamically, there is pressure depending upon acceleration, principally, but this pressure is equalized between the two jeweled bearings because of the unique arrangement of counterweights.

Accurate alignment of the locus of the point of contact between integrator wheel and glass disk is maintained by means of ball-bearing contacts with guide rails. The vertical guide rail on the lead-screw side serves as the true guide, since the four ball bearings on this side (two making contact with the vertical guide and two with the horizontal one) are fastened rigidly to the carriage. The single bearing making contact with the horizontal guide on the side opposite the lead screw is also fastened rigidly to the carriage. Thus, the weight of the carriage is supported by three points of contact with the horizontal guide rails. The two ball bearings running on the vertical guide rail opposite the lead-screw side are spring supported on the carriage, thus causing the carriage to be held against the vertical guide on the lead-screw side.

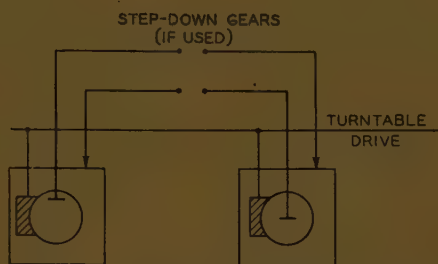


Figure 9. Mechanical interconnections of two integrator units for the generation of sine-cosine curves

This arrangement was used for the sine-wave growth tests of Table II

A lead-screw revolution indicator is shown in Figure 7, which is made up of two dials, one of which is graduated in hundredths of a revolution. The second is stepped down by means of gears to read complete revolutions over a range from +65 to -65. Thus, boundary conditions may be set to hundredths of a revolution. A split nut is pivoted in the carriage assembly and makes contact with the lead screw. Adjustable spring tension makes it possible to maintain the assembly free from back lash. A simple solenoid-operated clutch release is used which is positive in operation, and a push button is conveniently located so that boundary conditions can be set easily while the clutch is held in the released position.

Ventilating covers are provided for the thyatron tubes as shown in Figure 7. Screw adjustments for proper setting of the amplifier circuit constants are provided on the side of each unit.

Two limit switch controls on the integrator carriage are used in order to protect against possible overtravel and consequent damage. These are arranged in sequence, so that, as the normal range of travel is exceeded, the first switch stops the time motor. If travel of the carriage continues beyond this point; the second, which is an emergency switch, releases the clutch in the integrator lead screw.

Performance Data

The integrators were designed to operate at a maximum output-shaft speed of 1,000 rpm. One of the limitations on

maximum permissible speed is that of slipping between the integrator wheel and the glass disk. In order to determine whether or not this was an important factor over the speed range up to 1,000 rpm, numerous tests have been made. The test set-up used for this purpose and for the purpose of determining the overall mechanical accuracy is shown in Figure 8.

It will be recognized that, for each setting of the lead screw, there should be a fixed ratio between the number of revolutions of the output shaft and the turntable shaft. The revolution counters on these two shafts serve to add up the number of revolutions for each of these shafts and, when reduced to a common base of "equivalent revolutions" as required by the particular lead-screw setting, will serve as a means of evaluating the amount of slipping and over-all mechanical accuracy. For instance, since the lead screws have 16 threads per inch, and since the integrator wheel is two inches in diameter, there should be a 1:1 correspondence between the revolutions of the turntable shaft and the output shaft when the lead screw is set on either plus or minus 16. Thus, the integrator constant of

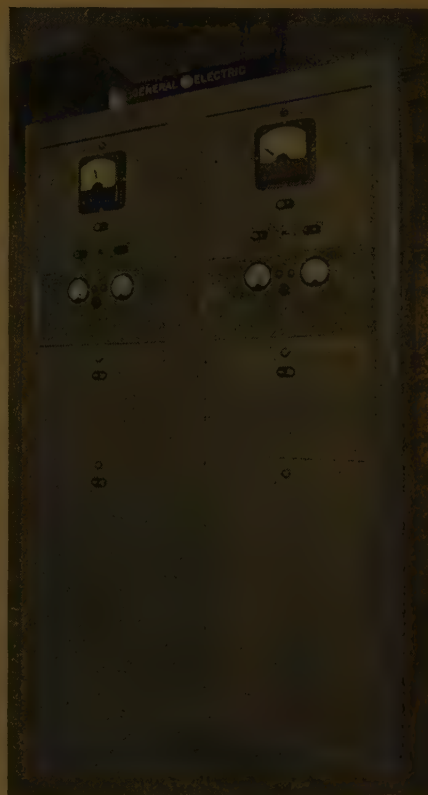


Figure 10. Control cabinets which house the power contactors, the regulated d-c power units for the amplifiers, the motor-driven field potentiometers of the Ward Leonard generators, and the two time-motor speed-indicating instruments

these devices is 16. Similarly, there should be just twice as many revolutions of the output shaft as of the turntable shaft when the lead screw is set on plus or minus 32, and so forth. Any difference between these nominal "equivalent revolutions" is due either to mechanical errors or slipping of the integrator wheel or both. Since any slip present should be a function of speed and acceleration, it seems reasonable to assume that, if there is no appreciable variation in the equivalent revolutions throughout the speed and load range, any deviation from a 1:1 correspondence based on equivalent revolutions is due entirely to mechanical errors and not to slipping. The test results summarized in Table I indicate that slipping does not exist to a measurable degree in these integrating units.

Another test which affords a measure of the over-all back lash of the follow-up system and connecting gear trains, an important criterion of performance, is shown in Figure 9. This system of connections will be recognized as that required for the solution of the harmonic equation

$$\frac{d^2y}{dx^2} = -\frac{1}{K^2G^2}y$$

in which K is the integrator constant and G is the gear ratio between the output



Figure 11. Representative adder unit

This low-friction design was found to require very small driving power



Figure 12. General view of the differential analyzer from the input and output-table side

There are four input tables and two output tables. The input-table drives may be cranked in both the horizontal and vertical directions. All input tables have polar co-ordinate attachments

shaft of each integrator. With one lead screw set on zero and the other at some arbitrary number of revolutions from zero at the start, if there were no back lash, the amplitude of succeeding cycles should equal this initial amplitude. However, because of the presence of back lash in the gears and follow-up system, the amplitude of successive cycles (number of lead-screw revolutions measuring displacement from zero) will increase. The rate at which this growth occurs in terms of revolutions per cycle is a measure of the over-all back lash and, therefore, serves as a good measure of performance. Typical sine-wave growth measurements of this nature are shown in Table II. Under the condition of high output-shaft speed and direct drive, the growth per cycle is most pronounced, as should be expected. As the step-down ratio is increased, the growth per cycle decreases rapidly and becomes relatively independent of integrator-wheel speed. The test results tabulated in Tables I and II were obtained with representative integrator units without the use of compensating means of any kind. When it is necessary to work with greater accuracies, suitable provisions can be made.

Control System

Speed control of the independent variable, ordinarily referred to as the time motor, is obtained by means of a Ward Leonard system which gives stepless speed control over the desired speed range, thus assuring the availability of optimum speed of operation at all times. The field potentiometer in the generator circuit is motor driven. This motor is controlled by means of push buttons at 12 convenient locations around the analyzer. A control panel is located at each input table and each pair of integrators. These panels include "start," "stop," "raise," "lower," and "reverse" buttons. They are so inter-

locked among the control stations that, if an operator at one station pushes "lower" button, the time-motor speed will be decreased, even though operators at other stations may be pushing a "raise" button.

At each station there is also a two-position "hold" and "neutral" switch. If an operator cranking an input table requires that a certain time-motor speed not be exceeded, the switch is thrown in the "hold" position. The speed of the time motor cannot be raised then from any control station. It can be lowered, however, at any control station simply by pushing a "lower" button. Thus, this interlocking control system provides that the station requiring the slowest speed will always take control.

Whenever a "stop" button is pushed and the time motor has come to a standstill, the motor drive for the generator field potentiometer automatically starts and brings the slider contact to the zero field potential position, thus assuring that, when an operator later pushes a "start" button, accelerations will not be excessive.

"Emergency stop" buttons are provided at convenient and readily accessible locations around the analyzer. By pressing this button all power to the analyzer, both alternating current and direct current, is removed. This serves to protect the machine against overspeed, and so forth, in case of a runaway or trouble whatever its nature may be.

At each pair of integrators there is a push-button control for energizing the light source and tube filaments. This control has a time-delay relay which is interlocked with the a-c supply, so that voltage cannot be applied to the motor and thyatron circuits until five minutes have elapsed from the instant of energizing the filaments, thus assuring adequate heating time for the thyatrons.

Two separate time motors are provided, one at each end of the analyzer bed. This permits the simultaneous solution of two problems, provided that the total number of integrators or input tables required does not exceed those available.

The use of two time motors requires that the controls at each station be applicable to either of the two time motors, depending on which one is being used in conjunction with the integrators or the input table associated with that control station. In order to meet this requirement, all wiring for each time motor is in duplicate in the bed of the machine with two outlets at each control station, one for each time motor. By means of a jack-and-plug arrangement the control panel

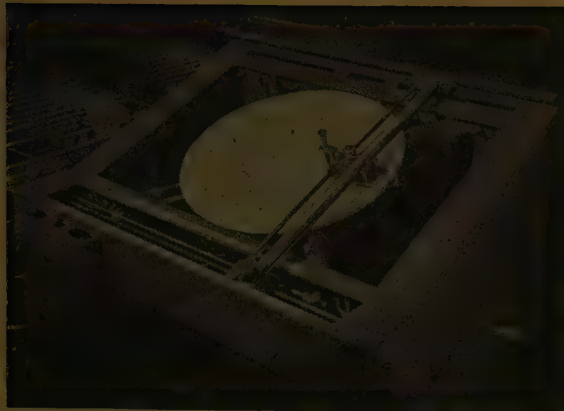


Figure 13 (left). Top view of input table showing the polar co-ordinate arrangement

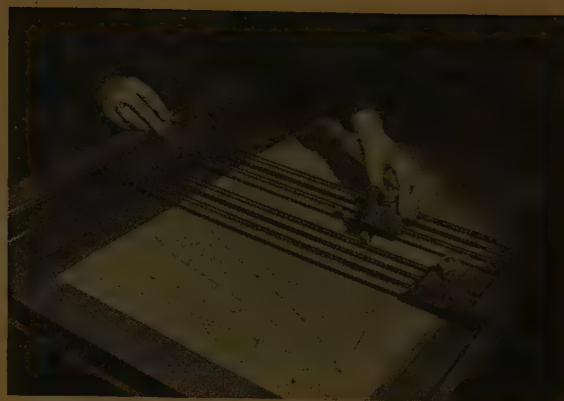


Figure 14 (right). Top view of output table showing the ink pen and the clear ink records

can be switched readily from one motor to the other as the requirements may dictate. This is shown in Figure 7, for example, applied to a pair of integrator units.

Figure 10 shows the control cabinets. They house the power contactors, the regulated d-c power units for the amplifiers, the motor-driven field potentiometers of the Ward Leonard generators, and the two time-motor speed-indicating instruments.

Miscellaneous Component Parts

A total of 20 differential gear assemblies or "adders" (one is shown in Figure 11) is available for use with the analyzer. These are of new design in which one of the major objectives was to keep friction to a minimum; this has resulted in light loads.

Helical gear boxes for right-angle drives are available. There are 50 right-hand and 20 left-hand drives.

Each input table (four are available) has both rectangular and polar co-ordinate drives. They can be used either as input tables for cranking in a function drawn in curve form, as manual multipliers, or as output tables for plotting solutions. Two output tables are located near the center of the analyzer. Each of these has two pencil carriages and will plot two functions simultaneously. The input and output tables are shown in Figure 12; and a close view of the input table arranged for polar co-ordinate drive is shown in Figure 13. Output-table records are obtained either by means of a fine-pointed brass stylus which is maintained lightly in contact with specially treated paper or by an inking pen. The ink records are easier to see and more permanent but do not permit as great accuracy in measuring. Figure 14 shows how distinct an inked output-table record may be.

Change gears totalling 440 are available in different tooth ratios required to

Figure 15. General view of the differential analyzer

In the background are the two control cabinets, the wall-mounted master power switches, and the cabinet containing the Induction-motor-driven Ward Leonard generators. The rack on the side accommodates all the accessories, such as gears, shafts, adders, and right-angle drives. The cabinet on the right of the accessory rack houses the air-conditioning system



Figure 16. Adjustable "dead-band" units



give adequate flexibility to meet practically all needs.

The main bed of the machine is essentially the same as that for the analyzer at the University of Pennsylvania. It is approximately 32 feet long, and over-all width 9 feet. Fourteen steel pedestals support the analyzer. Each of these pedestals rests on the concrete floor to which all are bolted. Figure 15 shows a view of the complete analyzer.

The stub shafts were aligned by means of the screw supports on the bus-shaft housings. These screws are very helpful in initially aligning the shafts for minimum friction and binding. Once aligned, the adjustment remains stable, and further adjustment has been found unnecessary.

Two "dead-band" units (Figure 16)

are available for the purpose of simulating intervals of no response or zero sensitivity, such as may be encountered in the solution of certain problems. Like those of the University of Pennsylvania, they are adjustable, so that the number of rotations of one shaft which can take place without the other one following it subsequent to a reversal of direction of rotation can be controlled. Once adjusted and inserted in the machine, the machine automatically includes the desired "dead band" in the solution.

Conclusion

Since the completion of this new differential analyzer several months ago, a number of important and urgent problems have been solved. The continuous

The MHO-Carrier Relaying Scheme

A Simplified Carrier Scheme for Long or Heavily Loaded Transmission Lines

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BECAUSE of the wartime problems of increased loads and shortage of materials, it is often necessary to put heavy loads on existing transmission lines rather than build new ones.

When transmission lines are heavily loaded it becomes difficult to retain relaying selectivity, because the currents and voltages which the relays measure are not sufficiently different to distinguish between faults and power swings except by adding auxiliary relays which check the rate of change of impedance. These auxiliary relays add complexity and cannot distinguish between power swings during which it is not desired to trip and an out-of-step condition for which it may be desired to trip.

This paper describes a new scheme which inherently distinguishes between the aforementioned swings and out-of-step conditions and, also, is very much

simpler than its predecessors. It is based on the same principles as the "Long-line" relay scheme described in a group of papers^{1,2,3} presented at the 1943 AIEE winter technical meeting, using phase-angle rather than impedance magnitude as a basis for distinction between load and fault conditions. It uses the same MHO unit, which measures admittance at about the phase angle of the protected line so as to provide a very high pickup on loads and power swings when set to operate on a fault at the end of the section. In this way the relays keep the transmission line in service as long as it can transmit power and remove it only when the systems swing apart so far that power cannot be transmitted.

Impedance Diagrams

In one of the aforementioned papers² it was shown that the locus of the impedance seen by a relay at a given location on a transmission line is a family of circles for different ratios of V_A/V_B where V_A and V_B are the terminal voltages at the ends of the line. The diameter of the circle tends to decrease as V_A/V_B departs from unity. It can be seen from Figure 1 that, if A were near the center of the system, V_A/V_B would decrease as the angle between V_A and V_B increased.

Consequently, for a given system condition, the actual locus of the impedance seen by the relay at A during the progress of a power swing is a line joining the proper points of angular difference between V_A and V_B on the proper circle for varying ratios of V_A/V_B .

The difference between this new locus and the first family of circles is that the equivalent generator voltages E_S and E_R (Figure 1) are used instead of the line terminal voltages V_A and V_B . Since E_S/E_R usually is close to unity, the new loci will be circles of large diameter for different values of E_S/E_R ; hence, usually it is permissible to dispense with the complex calculations of the rigorous method

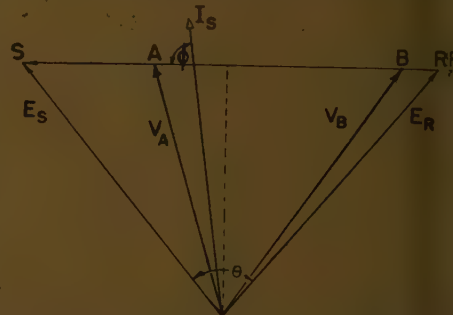


Figure 1. Vector diagram of a simple power system

and to consider all of the circles to be a single straight line passing through a point on the line-impedance vector separated from the origin by a distance approximately equal in ohms to the distance of the relay location from the electrical center. This is equivalent to assuming that the ratio of the equivalent generator voltages E_S/E_R is unity, and that there is no charging current or shunt loads. These simplifications have been used before,^{4,5} and result in the following relatively simple determination of the power-swing locus on an impedance diagram. They are permissible here, because the

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availability of this analyzer will result in greater knowledge and better understanding of many other technical problems, solutions of which heretofore have been possible theoretically but impossible practically.

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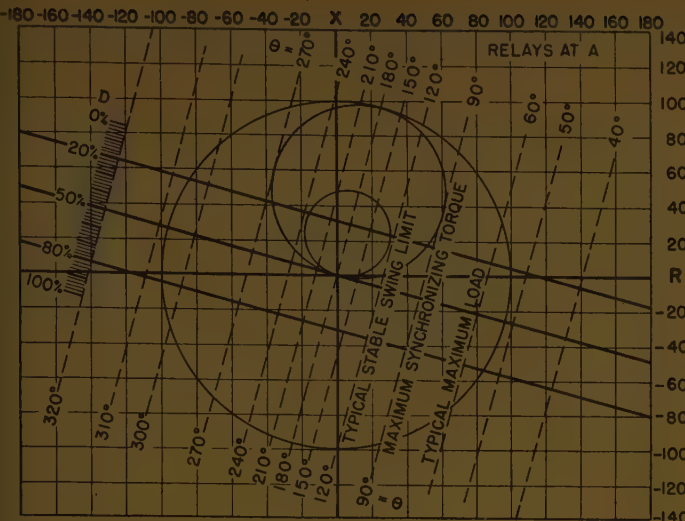


Figure 2. Impedance diagram for relays at various locations along a line connecting two systems, or machines, applicable to the special case in which $E_S = E_R$

possible inaccuracy is substantially tangential to the characteristic of the new relay and, hence, do not affect its setting.

The construction for obtaining the straight-line locus is as follows. Figure 1 is a simplified vector diagram of power transfer through a transmission line; it assumes that the power system has a uniform distribution of R and X and neglects capacitance. $S-A$ is the impedance drop of the system behind the bus at the sending end of the line and $R-B$ is the drop behind the bus at the receiving end. E_S and E_R are the sending- and receiving-end voltages which are assumed equal, and θ is the angle between them. I_S is the load current, and ϕ is the impedance angle of the transmission line. The input impedance at a point A is V_A/I_S which will change as θ changes. If V_A/I_S is plotted on an R and X diagram, it will appear as a straight line at right angles to the line impedance intersecting it at a distance from the origin equal to the distance of the point A from the electrical center. The vectorial equation of this line in terms of the angle θ between the generated voltages at the ends of the system is

$$Z_A = \frac{Z_S}{2} \left[(2D-1) - j \cot \frac{\theta}{2} \right]$$

where D is the per-unit distance of A from the leading end of the system (see Figure 2), and Z_S is the total impedance between the generator voltages E_R and E_S ; Z_A and Z_S are vectorial quantities.

When faults are plotted on a similar $R-X$ diagram along with the power-swing characteristic we obtain Figure 3 A. A fault appears instantly as a point on the line characteristic LL' . This line is at the angle $\phi = \tan^{-1} X/R$ where X and R

are the reactance and resistance of the transmission line. Point B is at a distance from the origin equal to the impedance of the line section being considered. Point B is for a solid metallic fault at the end of the section and, since most faults are flashovers and involve arcs which introduce a resistance, this is represented by adding such a component horizontally, the shaded area being the fault zone.

Loads, power swings, and out-of-step conditions are represented as impedance having different R and X values which move inward along a line at right angles to LL' and cut it at a point D such that AD is approximately the distance of the relay location from the electrical center. The values of θ are marked along the power-swing line and it can be seen very quickly what degree of system separation appears as the same impedance value as a fault.

When the characteristics of the different types of ohmic relays are plotted on an $R-X$ diagram, Figure 3 B is obtained, which shows that, for a given ohmic setting (90 per cent of line length AB) the reactance relay operates most readily, the impedance relay less readily, and the MHO unit much less readily than either. It can be seen that the MHO unit is simply a starting unit set for first-zone reach instead of third-zone reach.

When used with carrier blocking, however, it is apparent from Figure 4 B that the tripping area of the reactance relay is restricted considerably on power swings; out-of-step blocking, of course, prevents the distance elements from tripping in the horizontally shaded areas. In both cases, the electrical center has to be within the protected section to cause tripping, and tripping will only occur if

$X/R = \tan 75^\circ$
 No shunt load
 Shunt capacitance neglected
 D = distance of relay location from equivalent internal voltage of the leading end E_S , in per cent of total impedance from S to R
 The co-ordinates are scaled in per cent of total impedance from S to R , abscissas are resistance, ordinates are reactance

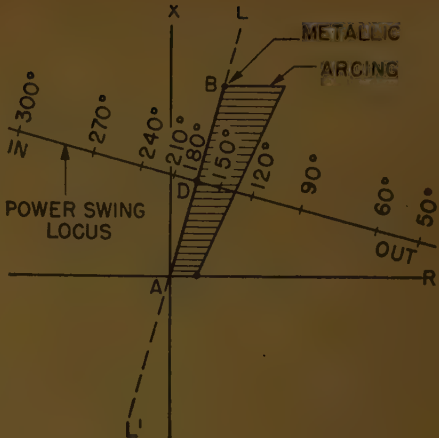


Figure 3 A. Resistance-reactance diagram of faults and swings

In = power incoming to bus
 Out = power outgoing from bus

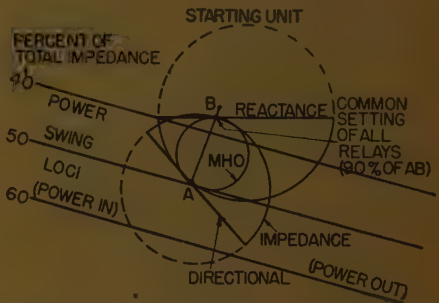


Figure 3 B. Characteristics of relays plotted on the R and X diagrams of a simple power system

the power-swing locus enters the tripping zones of the relays at both ends of the section. The carrier tripping area is shown shaded vertically in Figures 4 A and 4 B for the impedance and reactance relays. These diagrams are to the same scale, and illustrate that the tripping area is somewhat larger for the impedance relay because the radius of the characteristic determines the distance reach in the impedance relay, whereas only the diameter is involved in the case of the starting unit of the reactance relay.

Present Distance-Relay Carrier-Current Systems

It is apparent from Figures 4 A and 4 B that both of the present distance-relay-carrier combinations may limit unnecessarily the power that can be transmitted over a transmission line. The reactance relay limits this power by virtue of the fact that the starting unit must reach as far as is desired for the third-zone time step. The impedance relay, on the other hand, limits the load transfer because of the second-zone impedance unit, a type of relay unit that embraces more area on the impedance diagram than necessary.

The fundamental basis of the relay system herein described is the use of the starting unit of the reactance relay, but with its ohmic reach reduced to slightly greater than the line impedance, thereby encompassing a minimum area of the impedance diagram. A third-zone backup step may be obtained, if desired, by means described later.

To many operators, the principal objection to present-day distance-relay-carrier schemes is their complexity. The relay system to be described eliminates a substantial portion of this complication by

the relay, which represents the maximum power-swing condition for which it is desirable to stay in.

6. Be flexible enough to provide blocking on out-of-step conditions which may make this desirable.
7. Clear instantaneously all internal faults occurring during power swings or immediately after an external fault. Trip after a time delay if out-of-step blocking is used.
8. Allow reclosing after tripping on a fault, but not after tripping on an out-of-step condition.

The value of impedance representing item 5 depends upon either the maximum angle which can be tolerated from a sta-

in Figure 7. It will be realized, of course, that certain liberties have been taken in order to present the circuit in its simplest form for purposes of explanation.

The unit Z starts carrier for all phase faults by opening the carrier-start lead, and the unit M turns off carrier if the fault current is flowing into the section and completes the trip circuit up to the receiver-relay contacts. Then the removal of carrier current from the receiver relay allows it to trip the breaker.

A ground fault in the reverse direction opens the contacts GD_1 , starting carrier and causing the contacts R to remain open and prevent tripping. A fault in the tripping direction closes the contacts GD_2 to complete the trip circuit up to the receiver relay, which trips because no carrier is started.

The connections actually used are illustrated in Figure 8, and the operation of the relays is described in the following section.

Operation

A. PHASE FAULTS

Each phase has an impedance relay for initiating the carrier signal under abnormal conditions by circuit-opening contacts Z_1 , Z_2 , and Z_3 , Figure 8. This characteristic is shown as the circle Z in Figure 5.

An impedance element was selected for starting carrier because it will operate on power swings as well as faults. It has

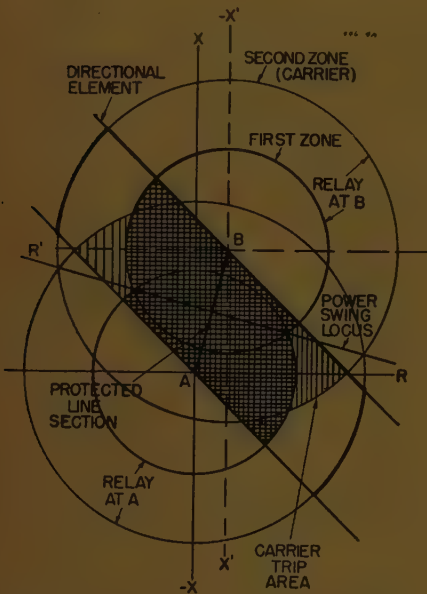


Figure 4 A. Impedance-relay characteristics plotted on R and X diagram so as to show combined tripping area

Vertically shaded area = carrier trip
Horizontally shaded area = distance trip

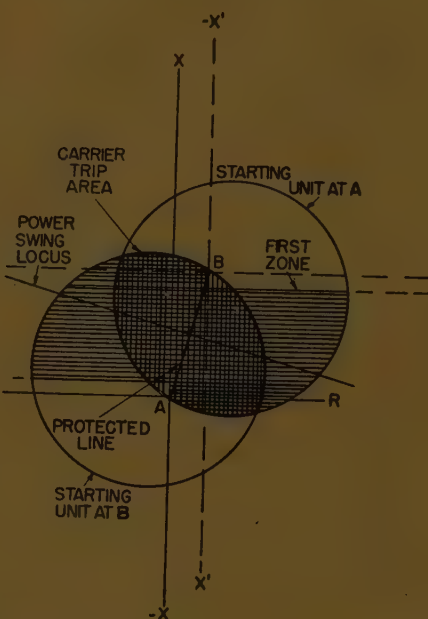


Figure 4 B. Reactance-relay characteristics plotted on R and X diagram so as to show combined tripping area

establishing a group of "building blocks" which provides, in most applications, a simple relay scheme. For the more difficult applications, additions may be made without changing the fundamental relay scheme.

Requirements of the Ideal Scheme

Most of the requirements have been stated already in the previous paper on long-line relays.² A more complete list is as follows:

1. Trip instantaneously for internal faults, arcing or solid, including three-phase faults at the circuit-breaker terminals.
2. Trip in delayed time for external faults.
3. Provide carrier blocking for external faults.
4. Not operate relays or carrier on loads up to the steady-state power limit.
5. Control tripping on system oscillations according to a value of impedance, seen by

bility standpoint or the angle which can be tolerated because of other limiting system conditions, such as low voltage.

Items 1, 3, 4, 5, and 7 are inherent in this scheme; item 2 may be achieved by backup relays as discussed later, and item 8 is accomplished by using the rate of change of impedance for blocking the reclosing circuit instead of the tripping circuit. A more detailed explanation of the operation of the relays now follows.

Characteristics of New Scheme

The original carrier-current idea⁶ was a very simple one, consisting of only a pair of directional relays which started carrier for external faults and made up a trip circuit for internal faults. This scheme returns to that idea in that it has but two relay elements—one for starting carrier, and one for the trip circuit.

The basic circuit is shown schematically

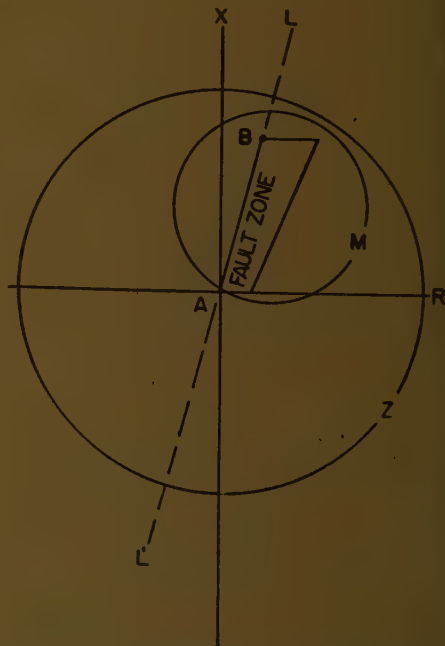


Figure 5. Characteristics of the MHO-carrier relaying scheme

M defines the tripping zone, Z , the carrier-starting zone

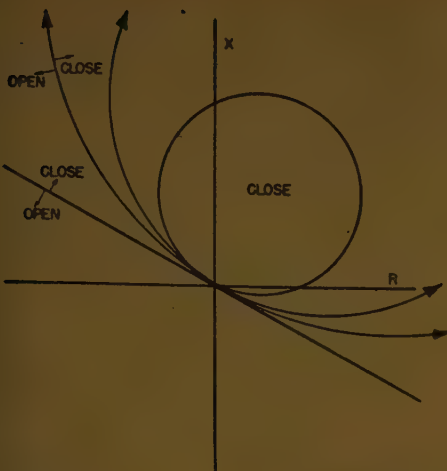


Figure 6 A. An impedance diagram illustrating how the straight-line characteristic of a directional relay becomes a circle as voltage restraint is added

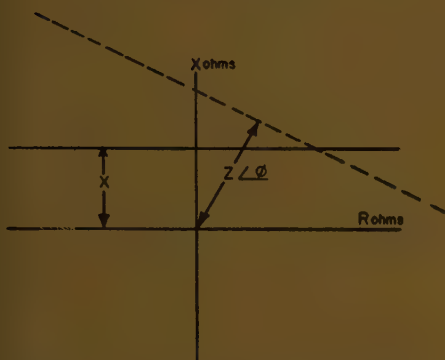


Figure 6 B. An R-X diagram of a reactance unit ($Z/90^\circ$) and an ohm unit (Z/ϕ)

Reactance unit—solid line
Ohm unit—dashed line

the advantage of being available, on medium-length lines, for preventing tripping or reclosure on out-of-step conditions. It can also be used for controlling a timing unit for backup purposes if the stepped distance-type backup is desired.

The second, or tripping, element in the relay scheme is an admittance element, called, for short, a MHO unit, since admittance is expressed in mhos; its characteristic is shown by circle M of Figure 5. This unit has been known for many years as the starting unit of the reactance-type distance relay.

A MHO unit is a directional element with voltage restraint added. As a directional element, it has maximum torque at some particular angle. As such, its characteristic is a straight line, as in Figure 6 A, operating to open contacts to the left of the line and to close them to the right. The addition of voltage restraint curls up the ends of the straight line into a circle, the size of which becomes smaller as the restraint is increased.

Each phase has a MHO unit, M_1 , M_2 , and M_3 , which stops carrier through an

auxiliary relay MX and makes up the trip circuit through a carrier-current receiver relay R , if the fault is within the protected section. In this respect the scheme is similar to earlier equipments.

B. GROUND FAULTS

The ground relaying has been considerably simplified by a return to the original idea of back-to-back directional relays, which is permissible for ground relays because there is no complication of power-swing currents entering at right angles to the fault currents. There is a complicating factor in the ground relaying, however, namely, the now known fact⁷ that residual currents can appear in the current-transformer circuits for phase faults not involving ground. These undesirable stray currents occur because the current

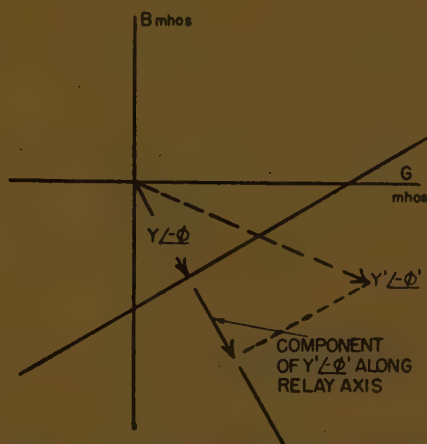


Figure 6 C. A G-B diagram of a MHO unit (Y/ϕ)

transformers do not balance out perfectly, and this, in turn, is primarily the result of premagnetization of the core, not to mention differences in manufacturing tolerances, et cetera. The usual settings require current transformers to be within less than one half of one per cent of each other, which is a severe requirement.

The use of a directional relay for starting carrier requires simultaneous errors of the proper phase angle of the polarizing source, as well as of the line current transformers, before a false operation can occur, since it operates on a product of the residual current of the three line current transformers and the polarizing voltage or current. With directional fault detectors throughout, no preference need be given to either the ground or phase relays. The idea of preference arose originally because the ground relaying had to be more sensitive than the phase relaying, and it was feared that load or power-swing currents would take control unless the ground were given preference. It has been dispensed

with now, because years of experience have indicated that false residual current may be produced by magnetized current transformers during phase faults, which may operate the ground overcurrent relay which turns on carrier and prevents tripping.

Carrier is started by a ground directional relay GD_1 (Figure 8) with normally closed contacts, which open for faults in the backward direction and remain closed for faults in the forward, or tripping, direction. The trip circuit is made by a similar directional relay GD_2 connected just oppositely with normally open contacts.

Settings of the Z and MHO Units

The impedance relay may be set to reach beyond the end of the line as long as it does not exceed the impedance value (see Figure 2) corresponding to maximum steady-state load. On short lines there will be no possibility of this, but on very long lines it is advisable to confine the relay setting to the line-section length, in order to avoid having carrier on for long periods. Reference to Figure 2 will show that, if the line could contain all the system impedance, the relay characteristic would reach to some point between the 50- and 60-degree lines which represents about the maximum separation that would be considered for steady-state conditions.

The MHO unit controls tripping, and, therefore, should not operate on power swings from which the system can recover. As stated before, the actual ohmic value representing this borderline depends upon system conditions, but it is known that above 90 degrees difference between the equivalent generator voltages the synchronizing power will decrease so that, while they may swing almost 180 degrees apart and still be stable, the limit is some value nearer 90 degrees.

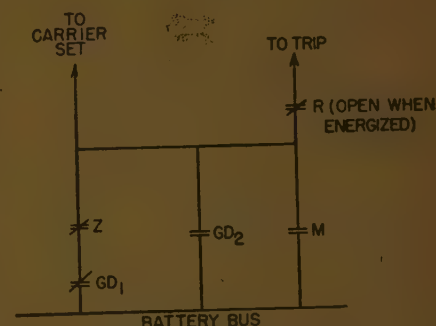


Figure 7. Simple elementary diagram of the MHO-carrier relaying scheme. The carrier starts when the circuit is opened and stops when the circuit is closed

See subcaption of Figure 8

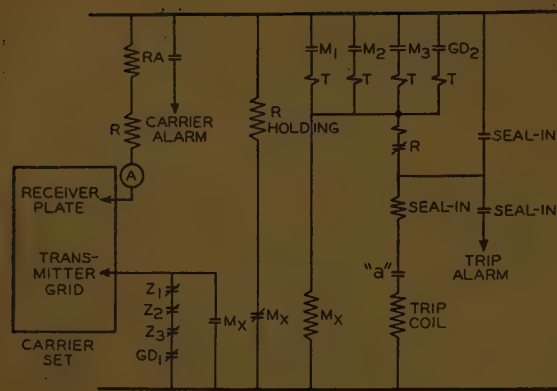


Figure 8. Complete elementary diagram of the MHO-carrier relaying scheme

A = ammeter
 GD_1 = ground directional relay (blocking)
 GD_2 = ground directional relay (tripping)
 M_1, M_2, M_3 = MHO relay units in phases 1, 2, and 3
 MX = MHO auxiliary relay
 R = receiver relay
 RA = receiver alarm relay
 T = target
 Z_1, Z_2, Z_3 = impedance-relay units in phases 1, 2, and 3

With all the system impedance in the line, if the MHO unit has maximum torque at the same angle as the line and is set to just cover the line, it will reach about the 90-degree separation line; if the line impedance is half the total impedance, it will reach to some point between the 120- and 130-degree lines. It can be seen from this that, on short lines and most long lines, the MHO unit will trip for faults and out-of-step conditions, but not power swings. On very long, very heavily loaded lines, some form of "blinders" will be required, such as the ohm units used in the long-line scheme,¹ which measure the component of impedance along the locus of the power swing so as to prevent tripping below a certain angle of system separation determined by a system study.

It will be seen from the foregoing that an application engineer can determine relay settings readily, as soon as he has decided the limits of steady-state load and the maximum angle permissible for power swings.

Description of Relays Used

A. THE PHASE RELAYS

Impedance Fault Detector. The characteristics of this relay often determine the maximum length of line that can be protected with this system of relaying. The longer the line, the less difference there will be between the impedance of a remote fault for which the relay should operate and the impedance for load conditions for which the relay should reset. In other words, the pickup of the relay and the dropout current should be as near together as possible.

The impedance unit Z used is of the induction-cylinder-type construction, using all eight poles to obtain a torque proportional to the operating current. This torque is perfectly smooth, free from any 60-cycle vibration—an inherent feature in the induction-cylinder construction.⁸ This feature is necessary because the unit

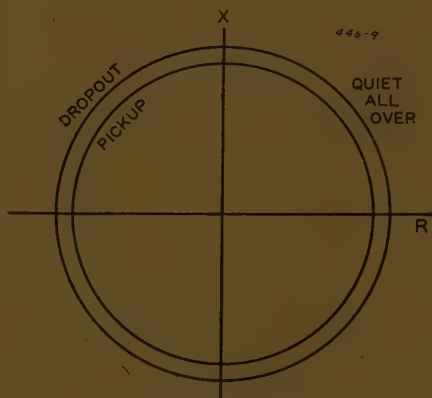


Figure 9. Characteristics of induction-cylinder impedance relay

may remain in the operated position for considerable periods of time when the systems are exchanging power at near the stable operating limit. Voltage restraint is provided by an attracted-armature-type construction with an adequately smoothed pull. This type of construction gives the most force for the least volt-ampere burden—practically a requirement for an impedance relay. Such a relay is seriously limited in this respect because the potential coil must stand rated voltage continuously and yet, when it is called upon to operate, must do so with only a small percentage of normal voltage. The usual disadvantage of an attracted-armature construction is that the force diminishes rapidly as the gap increases, being higher than the second power of the gap. This is minimized by operating with an air gap several times as large as the contact gap, and by using the minimum number of contacts; namely, a

transfer contact giving one normally closed and one normally open contact. By this means, the unusually high drop-out of over 90 per cent of pickup is obtained, Figure 9.

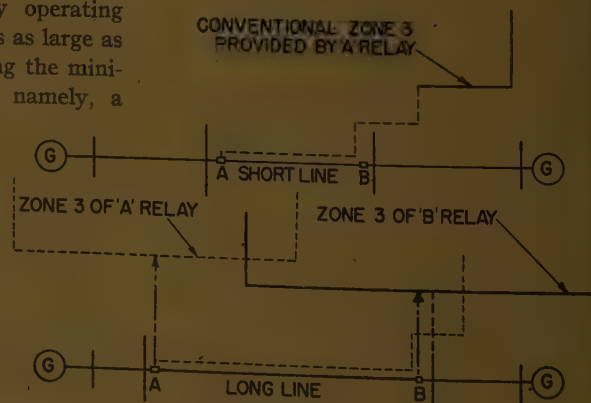
The MHO Tripping Relay. The MHO unit has the same four-pole induction-cylinder construction employed in the GCX directional distance relay, producing an operating torque proportional to $EI \cos (60^\circ - \theta)$ and a restraint torque proportional to E^2 . The angle of 60 degrees was selected as being near, but generally smaller than, the natural angle of a transmission line in order to minimize the tripping zone for power swings as explained under "Operation."

One of the most important features of the MHO unit is its memory action. No directional relay is expected to function with zero voltage, and this is the condition at which the mho circle passes through the origin. This difficulty is circumvented by making the polarizing potential circuit resonant at 60 cycles, so that the coil continues to have a substantial voltage across it for several cycles after the line voltage has been reduced to zero by a fault close to the bus. This feature cannot be shown on the two-dimensional $R-X$ mho circle diagram, but, if polarizing torque were plotted in a third dimension, it would have a sharp peak near the origin.

The MHO unit has double-wound current coils which give the same reach on phase-to-phase as on three-phase faults.

Origin of the Term MHO Unit. Why is the unit called a MHO unit? This sounds complicated, but we believe that it is actually the simplest name possible. The characteristic of the MHO unit is the circle of Figure 6 A, and whereas this shows graphically where the relay operates, there is no expression which states what the relay operates on. For 15 years we have had a reactance ohm unit which has the characteristic of the horizontal straight line in Figure 6 B. This unit operates whenever the reactive component of the impedance, measured in ohms, is less than its setting X . This character-

Figure 10. Tripping zones illustrating conventional and nondirectional long-line backup



istic can be tilted as shown by the dotted line, and then the unit operates whenever the ohmic component along the perpendicular line through the origin is less than the setting of Z/ϕ . Now, the MHO-unit characteristic is a straight line when plotted on an admittance diagram, as in Figure 6 C, and this immediately shows that it operates whenever the component of the admittance Y at the angle ϕ is greater than the relay setting.

B. GROUND RELAY

The ground directional units are likewise of the induction-cylinder construction available with either current or potential polarization. Their torque is proportional to the product of the two currents or to the current and the voltage, so that false operation would require an error in the polarizing source as well as a false residual current resulting from unequal current-transformer action. The lack of response to the d-c component of offset waves is an already well-known feature of the induction principle.

C. RECEIVER RELAY

A conventional permanent-magnet polarized receiver-relay unit is employed. It has spring-closed contacts and two restraining windings, one energized from the local battery, and the other energized by carrier received from either end of the line.

Usually, the first winding is energized through back, or normally closed, contacts of the mho-auxiliary unit MX in Figure 8, and holds the receiver-relay contacts open. When a fault occurs, the fault detectors turn on carrier, energizing the second winding by the carrier-receiver plate current. If the fault is within the protected section, the phase or ground directional relay M or GD shuts off carrier and de-energizes the battery winding so that the spring-operated contacts of the relay close and trip the breaker.

The advantage of this arrangement is that the second winding, the so-called d-c holding coil, keeps the contacts open until the trip circuit is completed. This coil is energized for reverse faults, thereby providing double assurance of preventing tripping.

Backup Protection

Backup protection is being considered separately because opinions differ as to the best type of relays, but almost everyone agrees that the backup relays preferably should be self-contained and separate from the carrier relays.

This is most easily achieved with the

ground relays for which the standard residual product or directional residual-overcurrent relays are very satisfactory. In the case of the phase relays, either directional overcurrent relays or stepped distance relays can be used, but in either case a MHO unit should be used for directional purposes, except in the case of very long lines on which the 20-degree ohm-unit blinders¹ are used.

The standard two- or three-step distance characteristic can be provided, though with some loss of simplicity of the scheme. The first step may be a standard reactance ohm unit set for 90 per cent of the protected section, using the MHO unit of the carrier-relay group as a starting unit; or it may be an entirely separate MHO unit, set for 90 per cent of the line and connected directly to the trip coil so as to provide a very reliable emergency

trip of the utmost simplicity. The chief purpose of the zone-1 distance step is to provide protection when the carrier equipment is out of service for maintenance.

In an emergency, instantaneous tripping on internal faults can be obtained while the carrier is out of service simply by short-circuiting the receiver-relay contacts with the carrier cut-off switch in the "off" position. This will enable the MHO unit to give instantaneous protection with carrier off; the fact that it is set for 110 per cent of the line ohms may not be as important as it sounds because, if there is generation on the bus, the actual reach in miles may be only one or two per cent beyond the end of the section, and the chance of a trip on an external fault in that small section would be very remote. If immediate reclosing is available, its significance almost disappears.

The second and third zones can be provided by a timing unit controlled by the impedance relay. The zone-2 contact is connected in parallel with the receiver relay so that, if the latter does not operate, such as when the fault is just beyond the bus but within the mho-unit range, the breaker will be tripped after a short delay.

On very long lines it is difficult to make the third zone reach far enough to do much good as backup, particularly if there is generation at the next bus. In such cases the relay nearer the fault can be used for zone 3, as shown in Figure 10, so that the voltage restraint on the relay is less by the drop in the line. The upper part of Figure 10 shows the usual arrangement of the time steps of distance relays and the lower part shows how the third step can be provided by the relay near the fault. The appearance of the relay characteristics to achieve this result are shown in Figures 11 A and 11 B, respectively.

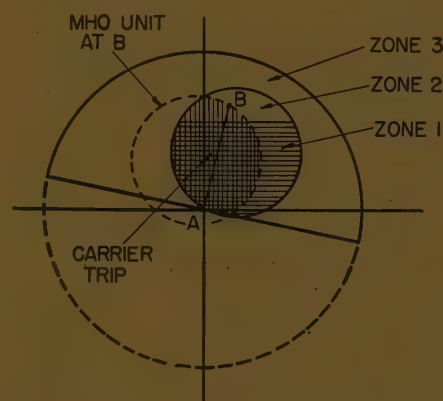


Figure 11 A. Conventional zone-3 backup for a short or medium-length line showing zones of protection provided by breaker A

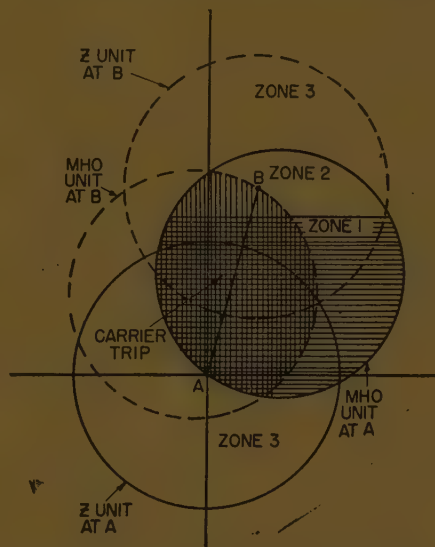


Figure 11 B. Nondirectional zone-3 backup for a long line, showing zones of protection provided by breaker-A relays and supplemented by breaker-B relays

Note that the zone-3 circle is the same size as Figure 11 A, which is determined by the maximum-load transfer. All the enclosed area represents protection

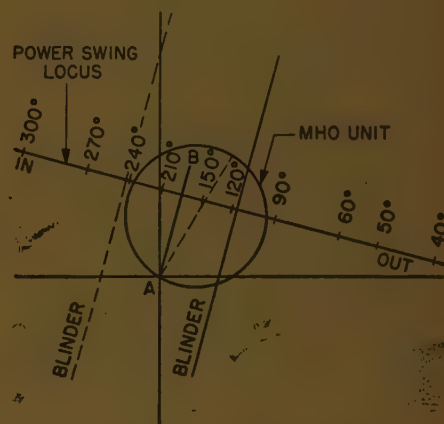


Figure 12. Blinders permit power swings to enter the MHO-unit circle

Note that the 60-degree MHO circle requires but one blinder on a 75-degree line

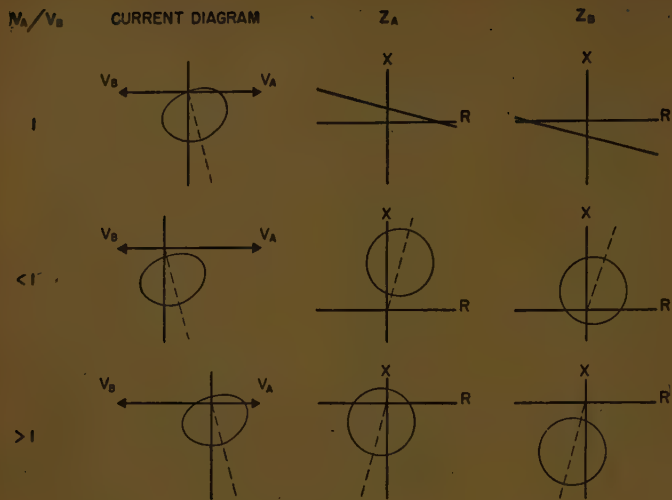


Figure 13 A. Characteristic loci of impedance as seen by relays during a power swing for different ratios of V_A/V_B

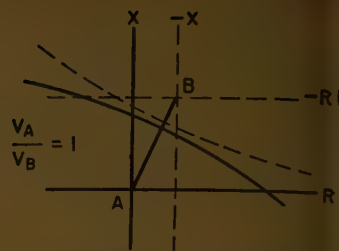


Figure 13 B. Locus of swing impedance viewed from the two ends of a transmission line

The solid line is seen from A and the dashed line from B

This simply means having the third-step timer contact going directly to the trip circuit and not controlled by a directional unit. The range of the third step, therefore, will be the ohmic setting of the impedance relay, which, on a long line, will be something less than the length of the setting. Thus backup time will be provided for external faults behind the bus and, also, over part of the protected section.

Very Long Lines

Figure 2 shows that the impedance seen by the relay during a swing decreases as the systems get farther apart until a point is reached where the relay characteristic is crossed and the tripping occurs. Since the size of the relay characteristic increases with the length of line covered, it can easily be seen that the tendency of the relays to trip during power swings increases with the length of line and the magnitude of the power swing.

Lines which are so long, or so heavily loaded, or both, that the line impedance during power swings is low enough to operate the MHO unit, require additional relays, which have been referred to as blinders, to prevent undesirable tripping. Lines in this category have more than half the total impedance between the ends of the system; that is, the line impedance must exceed the sum of the impedances beyond each of its extremities, so that the length of the line from the relay point of view depends on its length in miles and the generation at its terminals. Actually, such lines are usually over 200 miles long, though a heavily loaded line half this length could require the blinders.

These blinders are ohm units measuring a component of impedance along the power-swing locus, that is, about at right angles to the line characteristic.

These units have been described else-

where in detail.¹ They are similar to the standard *G-E* reactance-relay ohm unit except that they measure impedance at 20 degrees lead instead of 90 degrees lag. Their ohmic setting corresponds to a certain amount of load transfer or system separation, so that they may be set to trip on a power swing of a desired magnitude.

In some cases it is desirable to permit a separation of more than 120 degrees between the generated voltages when they are considered lumped at the ends of the line. Reference to Figure 2 shows that 120 degrees separation represents an ohmic value equal to 29 per cent of the total impedance between the ends of the system, which means that a MHO unit with maximum torque at the same angle as the line phase angle must not be set to cover more than 58 per cent of the system impedance without blinders; if one allows for a MHO-unit setting of 110 per cent of the section, the impedance of the protected section must not exceed $58/110 = 0.52$, that is, about half the total system impedance. If 150 degrees is considered the criterion, the MHO unit must not be set to cover more than 28 per cent of the total system impedance. For 90 degrees separation the figure is 100 per cent, which means that, no matter how long the line is, the MHO unit will not trip on swings or load conditions causing a system separation of less than 90 degrees. It should be remembered, however, that Figure 2 assumes straight lines for power-swing loci, whereas they are generally curves and variable, so that these percentage values are only approximate.

The corresponding figures for the impedance relay are half those of the MHO unit because the radius of the impedance-unit circle gives the same ohmic, or distance, setting as the diameter of the MHO unit. In other words, the impedance unit must be set for not more than half the

ohmic reach of the MHO unit in order to avoid operation on swings.

The minimum ohmic setting of the blinders is the maximum arc resistance expected. This can be understood readily, by reference to Figure 3 A. The maximum arc resistance⁹ is $8,750 L/I^{1.4}$ where L is the arc length in feet. For a 154-kv line the spacing will be about 14 feet and, if allowance is made for a light wind, the arc length may be 20 feet; at 500 amperes minimum current this would give an arc resistance of $8,750 \times 20/6,000 = 29.2$ ohms. Compared with this, a 100-mile line would have an impedance of about 80 ohms, but, of course, at a highly lagging angle.

It is sometimes unnecessary to use two sets of blinders, that is, six ohm units for preventing tripping or power flow in either direction. Usually only one set of three ohm units is required because it is generally possible to have the angle of the MHO unit less than that of the line, so that the relay may be vulnerable only in the direction of outgoing power, as shown in Figure 12.

Reclosing

Many of these long and/or heavily loaded lines are the lines between systems or parts of a system whose loss may result in the loss of other ties. Hence instantaneous reclosing after clearing faults may often be the means of saving the stability of the system.

It is preferable, however, to reclose only after faults and not after tripping on power swings or out-of-step conditions, because in the latter case the system is liable to be too far apart to stay in when reclosed. When a swing occurs it is caused by an abrupt change in load, generally an increase in load due to the loss of a source of generation. Reclosing is undesirable if the new load is greater than the load that can be reclosed successfully, that is, with stability after reclosure.

This selection of conditions suitable for

reclosing therefore can be made on the basis of the ohms along the power-swing locus representing the maximum steady-state load. A blocking relay with this ohmic setting can pick up an auxiliary relay with a slight delay which will prevent reclosing unless it is de-energized by the tripping relay before the auxiliary has had time to pick up, as would be the case of a fault where the blocking and tripping relays would operate simultaneously.

On short and medium-length lines the impedance relay that starts carrier can be used, also, to energize the auxiliary relay for blocking reclosure, because the impedance relay can always be set higher in ohms at any angle than the MHO unit which controls tripping and which can be used, also, for preventing the blocking.

On very long lines the impedance unit may not pick up before the MHO unit, and, in fact, both may be rendered ineffective by blinders. In order to ensure proper operation, in such cases, an additional single-phase unit is required to pick up the auxiliary relay and it must be of the same type as the tripping relay but with a higher ohmic setting. If the tripping relay is a MHO unit, the blocking relay must also be a MHO unit, so that it will pick up before the tripping MHO unit under all conditions. Similarly, if tripping is limited by a blinder, the blocking relay also must be an ohm unit like the blinder, but set for higher ohms. There is always a margin between the two like units, because the tripping unit must be set below the ohms of the maximum power swing, whereas the blocking unit has only to clear steady-state load conditions.

Where stepped-distance backup is used, the distinction often can be made very simply by arranging to reclose only after tripping by carrier relays. The line must be short enough to permit the impedance unit to be set farther than the MHO unit, so that carrier blocking will be available

on all power-swing conditions where the electrical center is within the protected section. In that case power swings will trip through the first-step MHO or reactance unit and will not reclose, whereas a fault will energize the carrier-relay trip circuit, also, and operate an auxiliary relay which will initiate reclosing.

Conclusions

The new scheme has a direct approach to the problem of relaying heavily loaded transmission lines, and has the virtue of considerable simplification over previous schemes.

It is applicable to all lines which normally would be considered long enough to justify the cost of carrier relaying.

Appendix

The following is a pictorial explanation of why the impedance loci appear as circles for a given ratio V_A/V_B . It has been explained already under "Impedance Diagrams" how the straight lines in Figure 2 are obtained for the condition $E_S = E_R$ and no shunt impedances. Figure 13 A shows a series of diagrams representing the loci Z_A and Z_B at stations A and B in Figure 1, A being at the leading, or sending, end of the transmission line AB.

The current diagrams⁴ would be circles if all the impedance were in the line, that is, if bounded by infinite busses. As the relay location approaches the electrical center the current locus approaches a semicircle. The voltage locus, however, has a complementary shape, so that the impedance becomes a circle.

In these diagrams capacitance has been neglected, but it can be seen easily that capacitance will tend to curl the straight lines for $V_A/V_B = 1$ downward, because they would tend to pass through a point on the $-X$ axis when V_A and V_B were in phase, so that the only current was charging current. Hence the effect of charging current would be to make all the circles below the R axis smaller and those above it bigger. For that reason the circles Z_A and Z_B would not be exactly symmetrical with respect to

each other. In other words, if Z_A and Z_B were plotted on the same diagram, as in Figures 4 A, 4 B, and 13 B, the two loci would not coincide because of the effect of capacitance.

In the preliminary diagrams of Figure 13 A, small circles are shown because V_A/V_B and V_B/V_A are large. Actually, the ratio would seldom exceed 1.25 and the circles would have a very large diameter, so that the part in the region of the power swings and the relay characteristics is more nearly a straight line.

A great deal of work has been done on graphical and analytical methods of obtaining the power-swing impedance loci. A quick method¹⁰ is to obtain the line impedance in the form of the equivalent T , and to calculate directly from it the radius and the ordinates of the center of the circle for the required ratio of V_A/V_B by vector algebra.

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Effect of Altitude on Impulse and 60-Cycle Strength of Electrical Apparatus

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ALTIITUDE is accompanied by a lowering of the air density, and, accordingly, it affects the performance of electrical apparatuses which depend on the air for operation. Thermal performance is affected because of the reduced heat dissipated by convection. Similarly the dielectric strength suffers a decrease with lower air density. The windage losses of machines and damping of instruments are less, but, in either case, the amount is not of consequence. At very high altitudes commutation may present a major problem and storage batteries become affected adversely. The interrupting capacity of some circuit-interrupting devices is also affected, the amount depending on various conditions. These are well-known instances where altitude is a factor in the operation of electrical apparatus.

Much research activity has been directed to these problems. From the beginning of high-voltage transmission, altitude was recognized as a factor affecting the operation of line and station apparatus.¹ Repeated efforts have been made to determine corona loss, and, to this end, several investigations have been conducted on transmission lines at high altitude.²⁻⁶ Contributions on the dielectric strength of air^{6,7,4}, and of electrical apparatus⁸ at normal and low air densities date from this early period. Similarly the effect of low air density on the thermal characteristics of electrical apparatus has been the subject of comprehensive investigations both from an engineering⁹⁻¹⁴ and a fundamental approach.^{15,16} The physical aspects and other practical considerations of the problem¹⁷⁻²¹ have been examined from time to time. As far as feasible the results of this work have found expression in the various apparatus standards and test codes.

Certain fundamental data are still

lacking although much progress has been made. This fact has been brought out in the Pacific Coast AIEE conference on the "Effect of Altitude on Rating, Testing, and Operation of Electrical Apparatus" in conference papers presented by P. L. Bellaschi, L. W. Robertson, and V. M. Montsinger and elsewhere.²² For instance, an immediate need is for impulse and 60-cycle data on actual station and line apparatus at low air densities corresponding to high altitude. This need has been recognized for some time, and the results of this investigation should therefore be timely and helpful in the field of application at high altitude.

Test Setup and Apparatus Tested

The tests were made in a sealed Micarta cylinder, 30 inches in diameter and 60 inches long inside. The test setup is shown in Figure 1. Either end of the cylinder may be removed, the apparatus for test enclosed, and the vacuum drawn. At the desired air pressure, voltage is applied to the high-voltage terminal which enters the cylinder at one end, the second terminal at the other end connecting to ground. A valve is set to leak air into the cylinder at a rate equal to the air removed by the vacuum pump; thus the air circulates through the cylinder and the inside pressure is main-

tained constant. Instruments give the essential data on the air. A barometer and a manometer provide measurements of the air pressure in the cylinder and outside. Wet and dry bulb thermometers measure the humidity and a thermocouple thermometer the temperature in the cylinder.

The tests cover some of the more common apparatus encountered in stations and on lines. These are listed in Table I. Figure 2, for instance, shows 15-kv and 69-kv bus and switch insulators typical of the standard apparatus that have been tested. Figure 3 illustrates a six-unit insulator string in the process of being lowered in the cylinder for test. The arrangement in Figure 4 for enclosing a 69-kv bushing indicates the flexibility of the Micarta cylinder in conducting the tests on the various station and line apparatus. In part of the tests as on the wood crossarm, shown in Figure 5, a porthole window was available at the ground end of the cylinder for visual observation of corona, flashover, and other effects. The smaller apparatuses were fitted with terminal electrodes in the manner prescribed in the usual dielectric tests. For large apparatus the clearance was limited, but in no instance did flashover occur other than over the apparatus or in the air. Thus the tests, truly and effectively were on the apparatus proper in a reduced atmosphere.

Method of Test

The procedure was to adjust the air density in the cylinder to the desired value and to condition the apparatus and the cylinder to the "new altitude." We found that for most apparatus the time required for the pumping sufficed to

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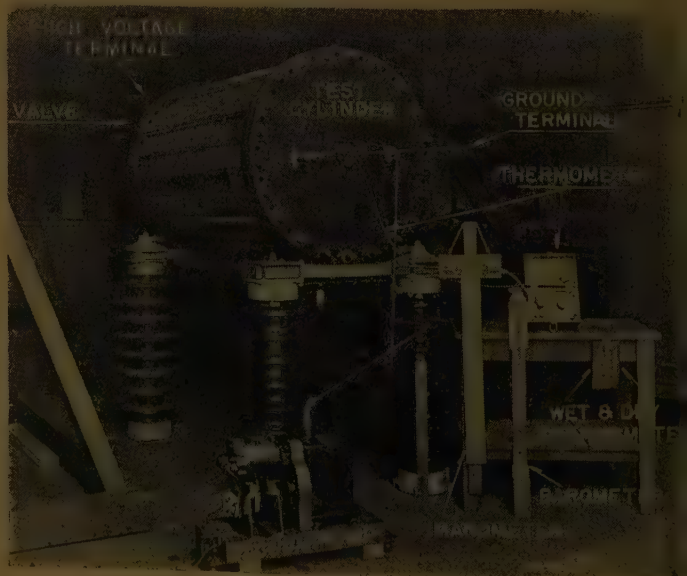


Figure 1. View of test setup

Table I. RAD Investigation of Station and Line Apparatus

Apparatus Tested	Type	Impulse Tests				60-Cycle Tests
		1 1/2x40 Microseconds		1,000 Kilovolts Per Microsecond		
		Positive	Negative	Positive	Negative	
5-kv switch and bus insulator	Station (outdoor)	X	X			X
9-kv switch and bus insulator	Station (outdoor)	X	X			X
9-kv condenser bushing	Station (outdoor)	X	X			
unit 10-inch-diameter suspension insulator	Station and line	X	X			
5-kv dry-type current transformer	Station (indoor)	X				
5-kv apparatus insulator	Station (indoor)	X	X			X
5-kv air-insulated transformer (Model)	Station (indoor)	X	X			X
66-kv air-insulated transformer (Model)	Station (indoor)	X	X			X
66-kv crossarm, four-foot section	Line	X	X			
4- and 12-inch rod gaps	General	X	X	X	X	
4-inch rod gap	General	X	X			
1/8-inch transformer oil (gap)	General	X	X			

condition the apparatus and the cylinder. In some tests, as on the transformer oil, constant air density was maintained several hours previous to the test. As stated before, a leak valve in combination with the vacuum pump provided a continuous flow of the air at constant pressure in the cylinder.

Tests were made from normal to low air densities and vice versa, with practically the same results. Most test data are limited from 1.00 to 0.50 relative air density (*RAD*), as this covers the practical range in altitude encountered on the earth's surface (Table II). However, some tests were extended below 0.10

RAD which corresponds to well above 40,000 feet and a few up to 1.50 *RAD*. All tests were made at room temperature, 20 to 30 degrees centigrade, and at 890 feet (Sharon, Pa.).

The data are reported in terms of the relative air density, given by the formula

$$RAD = \frac{0.392 b \text{ (millimeters)}}{273 + t \text{ (degrees centigrade)}}$$

in which *b* is barometric pressure and *t* is temperature. The absolute humidity at the low *RAD*'s is, essentially, the ab-

solute humidity at atmospheric pressure reported for each series of tests multiplied by the *RAD*. The reason for this lies in the fact that for a given mass of air, the water content is the same inside and outside the cylinder.

The technique of testing and measurement fully complies with the recognized methods described in AIEE Standard 4 (1943). In this respect the Sharon high-voltage laboratories are well equipped for both 60-cycle and impulse testing. For instance, an impulse generator of 0.016 microfarad at 3,000 kv and correspondingly higher capacitance for lower test voltages was available. All impulse measurements were recorded with the cathode-ray oscillograph. Typical oscillograms are shown in Figure 15.

Full-Wave Impulse Tests

The critical flashover data for 69-kv and 15-kv switch and bus insulators are plotted in Figure 6. Each point represents the crest of a $1\frac{1}{2}\times 40$ -microsecond voltage impulse which caused flashover on 50 per cent of the applications. From normal to 0.47 *RAD*, the lower limit of these tests, each set of points practically determines a straight line. The voltage over this range is directly proportional to the *RAD* plus a constant. One curve extends to 1.23 *RAD* which at 760-millimeter barometric pressure would correspond to -51 degrees centigrade. These curves are typical of the tests made on other outdoor station apparatus and on line insulators.

One point of interest is the longer time to flashover observed at low air density.



Figure 2. Typical switch and bus insulators tested

- A. Apparatus insulator, 15-kv class, indoor type
- B. Switch and bus insulator, 15-kv class, outdoor type, National Electrical Manufacturers' Association standard
- C. Switch and bus insulator, 69-kv class, outdoor type, NEMA standard



Figure 3. Test arrangement for suspension insulators

Insulator string being lowered into cylinder for test



Figure 4. Test arrangement for bushing

Table II. Atmospheric Conditions at Various Altitudes

Elevation Feet Meters	Standard Atmosphere*		Isothermal** Atmosphere		Conditions on Earth's Surface	
	Barometric Pressure (Millimeters)	Temperature (Degrees Centigrade)	Temperature = 0°C RAD = 0.392b 273 + t	Barometric Pressure (Millimeters)	Temperature† (Degrees Centigrade)	Humidity Vapor Pressure (Millimeters)‡
0.. 0.....	760	15.....	1.03	760	20.....	15.45
3,281.. 1,000.....	674	9.....	0.94	670	10.....	10.60
6,562.. 2,000.....	596	2.....	0.85	592	7.....	7.40
9,843.. 3,000.....	526	-5.....	0.77	522	2.....	5.10
13,120.. 4,000.....	462	-11.....	0.69	461	-3.....	3.50
19,690.. 6,000.....	354	-24.....	0.56	359	-14.....	1.70
26,250.. 8,000.....	267	-37.....	0.44	280		
32,800.. 10,000.....	198	-50.....	0.35	218		
39,370.. 12,000.....	145	-55.....	0.26	169		
49,210.. 15,000.....	90.7	-55.....	0.16	116		
65,620.. 20,000.....	41.4	-55.....	0.075	60		

* National Advisory Committee for Aeronautics reports 218 and 538.

** Smithsonian Meteorological Tables, numbers 56 and 57.

† Reference 20, "Mean Temperature for the Entire United States."

‡ References 17 and 19, typical data for standard reference (15.45 millimeters, vapor pressure) at the earth's surface.

In Figure 15 are typical oscillograms. Thus, for the 69-kv bus and switch insulator and a negative wave, the time to flashover at 0.97 RAD is seven microseconds and at 0.47 RAD, 27 microseconds. Present concepts of the breakdown mechanism appear to be in accord with this effect.

The tests in Figure 7 were made on a 15-kv dry-type current transformer rated 100/5 amperes. This apparatus depends for its strength on tape or layer insulation in combination with the air. Flashover determines the insulation level. The curve is typical for similar indoor station apparatus. The flashover at 0.50 RAD again is somewhat better than one-half the voltage at 1.00 RAD.

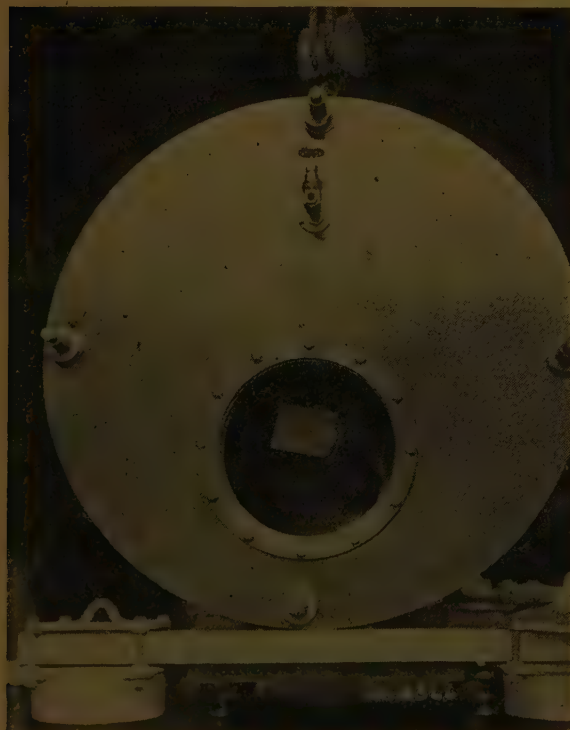


Figure 5. Testing of wood crossarm

Cylinder provided with port-hole window for viewing test

Figure 8 presents typical data for 24-inch, 12-inch, and 6-inch rod gaps. Some of these tests cover a range from 0.10 to 1.50 RAD. The variations are much as would be expected for rod gaps. For the most part the curves are straight lines. Tests at low RAD show long times to sparkover as noted for apparatus. Other unusual effects were observed; for instance, below 0.05 RAD the collapse of the voltage would be abrupt on some tests and in others slow.

Wood is used extensively in transmission and distribution and, lately, in substations. For this reason, it was decided tests should be made. New, seasoned-fir crossarms for a 69-kv line were cut in lengths suitable to enclose in the

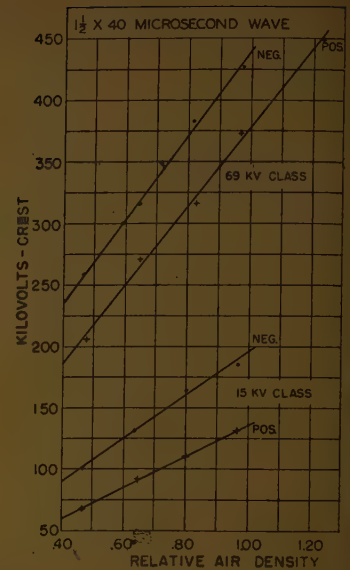


Figure 6. Critical-impulse flashover of standard switch and bus insulators

Atmospheric conditions
Temperature, 25 degrees centigrade
Barometer, 740 millimeters
Humidity, 16 millimeters

cylinder and four-foot sections tested. The data, given in Figure 9, substantiate further the fact that wood is quite variable on impulse. However, the curves show clearly that the impulse strength of wood suffers a reduction with RAD.

The peculiar behavior of wood is evidenced from these tests. Time to flashover or breakdown for wood is 2 to 3 microseconds at normal RAD. At 0.50 RAD critical flashover occurs at 12 to 15 microseconds, and this would indicate that air is a primary factor in the breakdown. When breakdown occurs in the air, the voltage collapses suddenly to zero. In some of the tests the collapse is slow, followed by a residual voltage which indicates a discharge in the wood somewhat in the manner of an arrester. These effects are indicated in oscillograms.

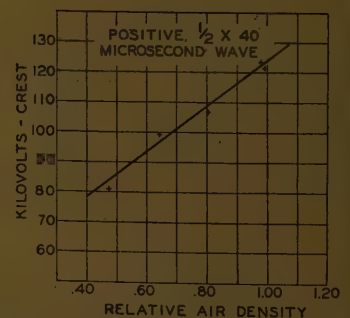


Figure 7. Critical-impulse flashover of 15-kv indoor dry-type current transformer

Atmospheric conditions
Temperature, 27 degrees centigrade
Barometer, 730 millimeters
Humidity, 12.5 millimeters

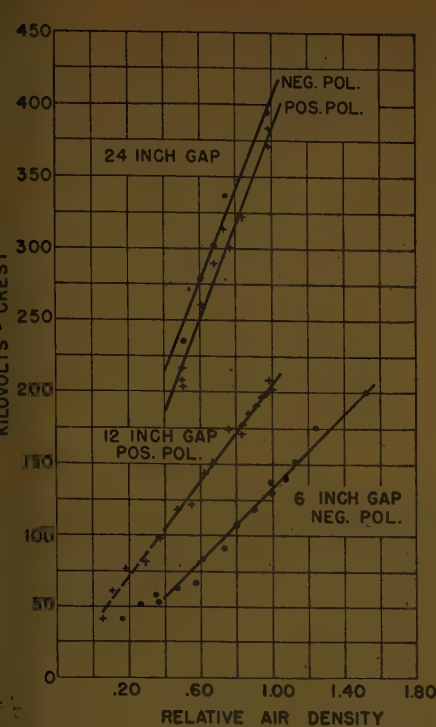


Figure 8. Critical-impulse sparkover of rod gaps

Atmospheric Conditions

Gap	Polarity	Barometer (Millimeters)	Temperature (Degrees Centigrade)	Humidity (Millimeters)
24	negative	730	25	17
24	positive	734	25	19
12	positive	747	20	8
6	negative	733	18	12

grams E of Figure 15. The streamers at the low RAD, often extending over a long section of the wood without completing the breakdown, were plainly visible. The splintering was moderate as the currents were limited to a few thousand amperes.

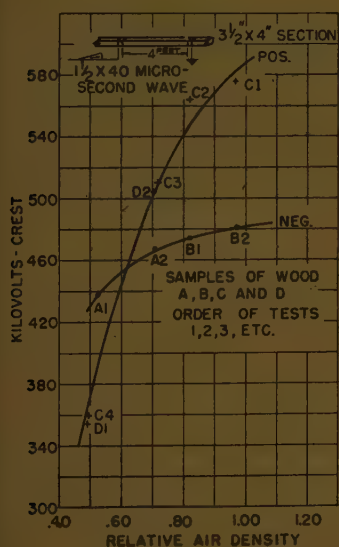


Figure 9. Critical-impulse flashover of four-foot fir crossarm

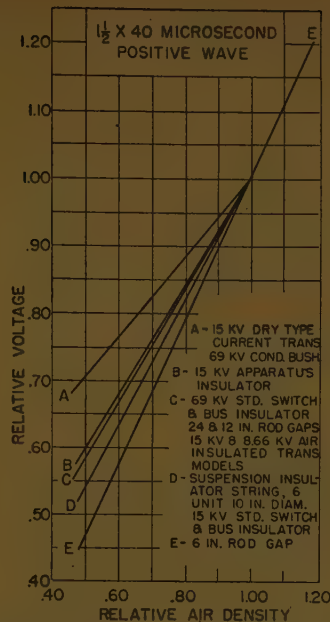


Figure 10. Effect of air density on critical-impulse flashover and sparkover

At the high RAD all tests were accompanied by vigorous noise upon flashover or sparkover. At 0.50 RAD the noise would dwindle materially and practically vanish at very low densities.

Beside testing typical apparatus, tests were made on insulation of interest in engineering. In Figures 10 and 11, these and the previous data are plotted in the convenient form of correction factors. For the apparatus in air the curves cluster close to a line that runs from unity through zero. A conservative procedure would be to consider the impulse level of station and line apparatus in air as directly proportional to the RAD after it is recognized that the positive impulse generally determines the

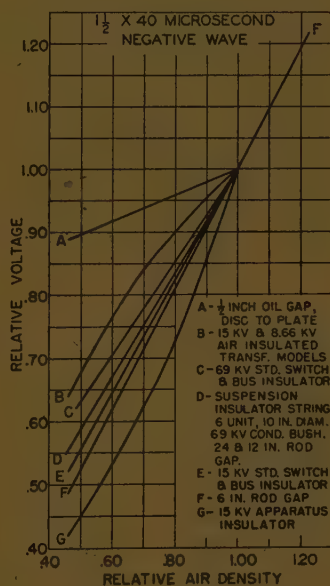


Figure 11. Effect of air density on critical-impulse flashover and sparkover

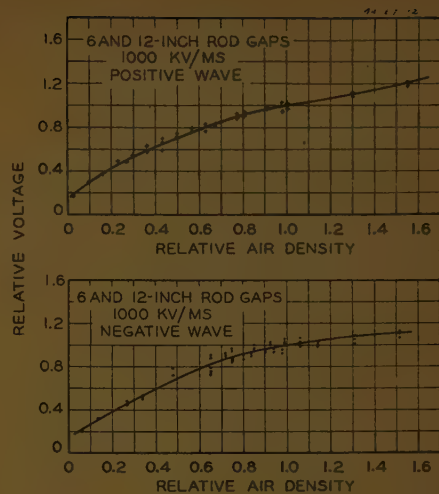


Figure 12. Front-of-wave sparkover of rod gaps

Points are typical of the spread and represent values for 12-inch rod gap

Atmospheric conditions

Temperature, 22 degrees centigrade

Barometer, 742 millimeters

Humidity, 9.0 millimeters

level. For a most exact evaluation of the correction factors reference should be made to Figures 10 and 11.

Curve A of Figure 11 shows a reduction of ten per cent in the strength of oil from 1.00 to 0.50 RAD. This is not a major reduction considering that the corresponding altitude is from sea level to practically 20,000 feet. Solid insulation impregnated in oil is probably affected even less. For this reason, station and line apparatus immersed in insulating liquid can be considered as little affected by altitude. At the very high altitudes the strength of solid and liquid insulation may have to be examined, particularly, if for any reason the low air density affects the condition of the insulation.

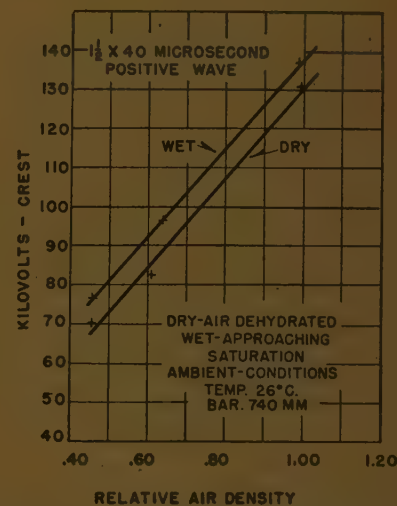


Figure 13. Effect of humidity on critical-impulse sparkover of six-inch rod gap

Front-of-Wave Impulse Tests

Direct strokes of lightning are an important consideration in the co-ordination and protection of apparatus.²³ Front-of-wave impulse data at low air densities are desirable, since lightning is present at high altitudes.²⁴ Accordingly, tests were made on 6- and 12-inch rod gaps, and the data are given in Figure 12 in the form of correction factors. F of Figure 15 is a typical oscillogram.

From normal to 0.50 RAD the correction on an average basis is 0.5 per cent per 0.01 RAD; that is, at 0.75 RAD the correction factor is 0.87. Within 0.90 to 1.10 RAD the correction is less, 0.35 per cent per 0.01 RAD. Within this limited RAD range a similar correction for short impulses has previously been reported.²⁵ For practical purposes the curves in Figure 12 can be considered applicable to high-voltage apparatus which have essentially a rod-gap type of characteristic.

Humidity and Other Effects

Comparative tests were made on the six-inch rod gap to determine the effect of humidity at low air densities. First, the tests were made in dry air, supplied from a calcium-chloride-phosphorous-pentoxide desiccator. The tests were repeated in a humid atmosphere produced by a pan of water in combination with cloth wicks introduced into the test cylinder. All tests were with a $1\frac{1}{2}$ x40-microsecond positive wave. The results are plotted in Figure 13.

The same vapor pressure maintains for normal and low air pressures.²⁶ We estimate the humidified air attained 0.80-inch mercury vapor pressure or

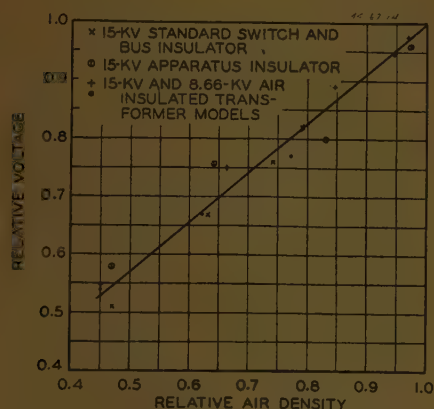


Figure 14. Effect of air density on critical 60-cycle flashover

Atmospheric conditions

Temperature, 29 degrees centigrade
Barometer, 735 millimeters
Humidity, 18.3 millimeters

better. From the two curves we note a constant difference of eight kilovolts throughout. It appears that physically the humidity has a fixed effect. Thus on a per cent basis the increase in strength from dry air to 0.80-inch vapor pressure is nearly twice as great at 0.50 RAD as at 1.00 RAD. On the strength of these data the humidity corrections determined at sea-level conditions cannot be applied at high altitudes but require a scaling up in an inverse relation to the RAD. Additional tests are desirable to establish these relations fully.

rays, ultraviolet rays, and similar ionizing agents upon the strength of electric apparatus. At the high altitudes particular these effects may require examination.

60-Cycle Data and Corona

As stated before, 60-cycle studies at low air densities date from the beginning of high-voltage transmission. In this investigation tests were made mostly with apparatus typical of indoor type. The results are given in Figure 14. Break-

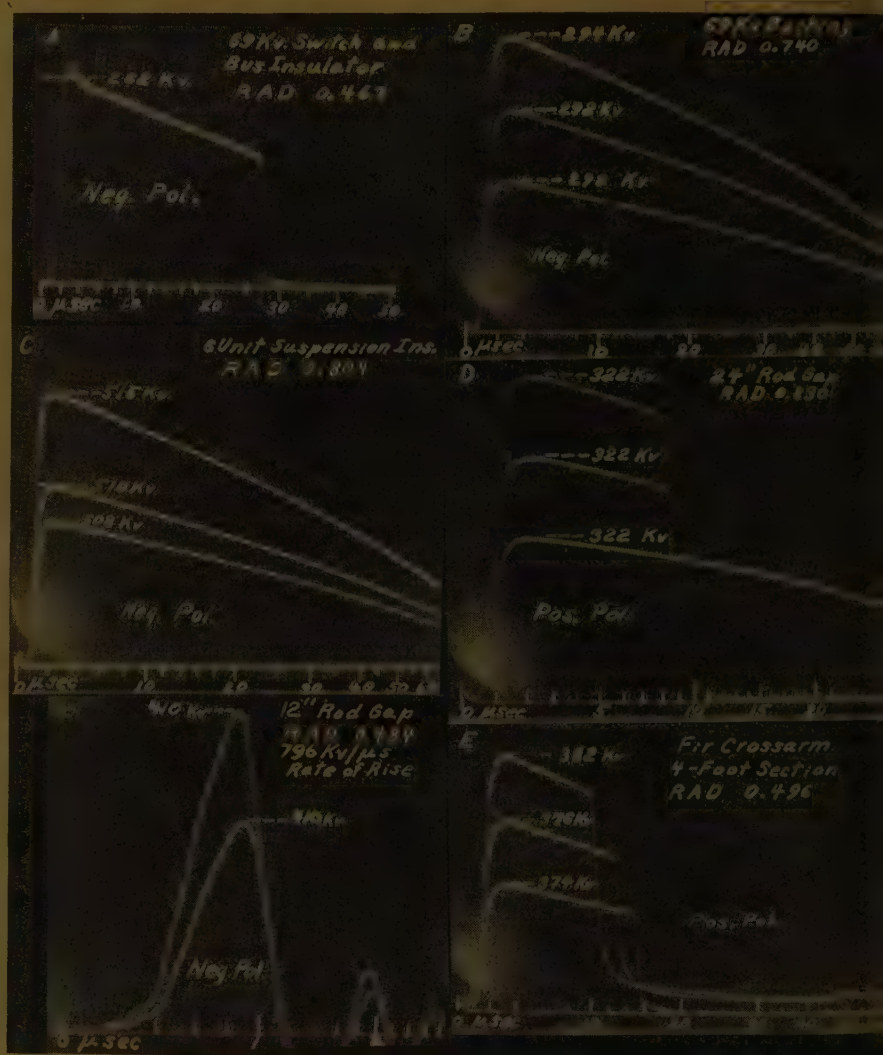


Figure 15. Typical oscillograms of impulse voltages

However, humidity drops with altitude so that actual conditions mitigate against a large over-all correction. On the other hand, the drop in temperature with altitude improves the strength, but again the effect is secondary (Table II). Aside from rain, snow, and so forth, there may be other factors; for instance, little apparently is known of the effect of cosmic

down data for a uniform field where temperature controlled the RAD from 1.0 to 0.50 likewise follow this curve. From all data at hand the 60-cycle strength of apparatus practically can be taken directly proportional to the RAD. In applying or testing apparatus at high altitudes it seems fundamental that the voltage ratings should conform to this relationship. Where the insulation margins are inherently large and there are no other limitations, as is the case for

me of the low-voltage equipment, no rating appears necessary other than possibly at the very high altitudes.

We had planned to investigate corona at low air densities, particularly its effect on insulation and radio noise, but other activities have deferred these tests. For instance, there is the possibility that apparatus may operate at high altitude with more apparent corona than would be permissible at sea level. The dry atmosphere at high altitude may also contribute beneficially to longer insulation life. The question of corona losses on lines is of particular interest to transmission engineers, and this also may require further examining in the light of the actual conditions prevailing at the high altitudes. These are some of the corona effects on which more study and testing may be well worth while.

Summary

The air strength of electrical apparatus to long waves ($1\frac{1}{2}\times 40$ microseconds) is essentially proportional to the *RAD*. The impulse strength of apparatus applied at high altitudes and exposed to lightning should be rated accordingly.

The *RAD* corrections for front-of-wave impulses (1,000 kv/microsecond) are one half and less than one half of those for long waves.

Sixty-cycle strength and corona are also affected in direct relation to the *RAD*. Voltage ratings naturally should recognize this.

The oil strength of apparatus is practically unaffected by altitude.

Data on the effect of humidity are presented. Other influencing factors that may be present at high altitude are

discussed. Corona effects may need more attention.

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A 500,000-Kva 7.5-Kv Air Circuit Breaker for Steel-Mill Service

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Synopsis: A self-contained air circuit breaker for a rating of 500,000 kva at 7.5 kv has long been regarded as a desirable goal. Recent developments in magnetic-type air circuit breakers have indicated the economic feasibility of similar designs for ratings higher than previously attained. The development of a 500,000-kva 7,500-volt magnetic air circuit breaker is described. A description of the breaker and the peculiar design problems are presented. Test data with oscillograms are shown.

WITH the advent of the first 15-kv power air circuit breakers for central station service in 1929,^{1,2} it was soon

recognized that an air circuit breaker was much more desirable for highly repetitive steel-mill motor switching than was the conventional equipment universally used at that time. Interrupting tests showed that the air circuit breaker could withstand many operations on considerable power without requiring maintenance, as compared to the high

maintenance necessary on oil switching equipment of that period. This was somewhat to be expected in view of the fact that low-voltage air circuit breakers and contactors had demonstrated this ability for years. It was also believed that the air circuit breaker was highly desirable for steel-mill-substation service because of the additional severity of steel-mill operating conditions, as com-

parisons with oil switching equipment. The first breakers of this type, installed on large reversing mill motors in 1932, are still doing duty at the rate of about 50,000 operations per year.

The success of these breakers and of the companion designs for 2.5-, 5-, and 15-kv ratings has been largely responsible for a general trend toward air circuit breakers in this range. However, the problem of interrupting higher currents at higher kilovolt-ampere ratings disclosed economic limitations in the metal-plate deion principle indicating limits in current interrupting rating beyond which construction would be too expensive for general use. Thus, the ratings of 250,000 kva at five kilovolts and 500,000 kva at 7.5 kv, involving currents of 30,000 to 45,000 amperes, were considered beyond the range of economic use of the metal plate deion principle. The development of a new principle of arc interruption in air^{3,4} made possible the attainment of higher short-circuit current interrupting ability at 2,500 volts than was practical with previous designs. This new principle made use of magnetic diffusion effects with plates of refractory insulating materials.

Through considerable experimental work and study of this principle, five-



Figure 1. 7.5-kv 250,000-kva deion air circuit breaker for metal-clad switching equipment as widely applied in steel-mill service

recognized that an air circuit breaker was much more desirable for highly repetitive steel-mill motor switching than was the conventional equipment universally used at that time. Interrupting tests showed that the air circuit breaker could withstand many operations on considerable power without requiring maintenance, as compared to the high

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Figure 2. Five-kilovolt 150,000-kva magnetic deion air circuit breaker

pared to the duty on corresponding equipment in central-station service.

Realizing these facts, a 250,000-kva 7.5-kv deion air circuit breaker of the metal-plate type was made available in 1932, designed to meet the rigorous demands of steel-mill switching service, for either substation or motor switching duty. Illustrated in Figure 1, this breaker has been widely and successfully applied in some of the largest steel mills in the in-



Figure 3. Five-kilovolt 250,000-kva magnetic deion air circuit breaker

kilovolt breakers of 150,000-kva and 250,000-kva interrupting ratings were developed⁸ as illustrated in Figures 2 and 3. The short-circuit current which must be interrupted by the 250,000-kva five-kilovolt breaker is 35,000 amperes at the commonly encountered distribution voltage of 4,150. Figure 4 is an oscillogram showing the interrupting by this breaker of 40,000 amperes at 4,020 volts restored, on a single pole, which shows considerable margin for a three-phase rating of 250,000 kva in the five-kilovolt class. This development contributed greatly to the technique of interrupting high currents at higher voltages than previously deemed feasible for a self-contained air circuit breaker.

However, a 500,000-kva breaker for 7.5 kv still remained to complete the



Figure 4. Oscillogram showing interruption of 40,000 amperes at 4,020 volts restored on a single pole of a five-kilovolt 250,000-kva magnetic deion air circuit breaker

Equivalent three-phase kilovolt-amperes—330,000 kva

line of self-contained-air circuit breakers. The breaker herein described completes the need previously indicated.

The general requirements which should be set by a breaker of this rating are:

1. Interrupting capacity of 44,000 amperes at 6,600 volts, three phase.
2. Full interrupting rating at 25 cycles as well as 60 cycles which is often required.
3. General ruggedness and freedom from excessive maintenance requirements.

4. Insulation level adequate for the new insulation standards of 95-kv impulse strength and 36-kv one-minute 60-cycle test.
5. Readily suited to use in the compacted space of metal-clad switching equipment.

The problem of interrupting heavy-current arcs in a restricted space in air is more difficult at the higher currents and especially at the higher voltages. Twenty thousand amperes does not now present a very serious problem, but, 40,000 amperes presents much more than double the 20,000-ampere job. The interrupting of 44,000 amperes at 7.5 kv presents problems in arc control and space de-

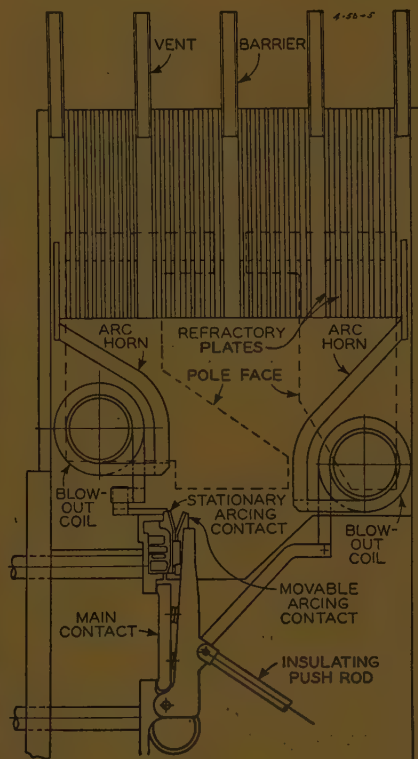


Figure 5. Schematic illustration of construction of 500,000-kva 7.5-kv magnetic deion air breaker

ionization far beyond those dealing with more moderate currents.

The initial drawing of the arc on the arc tips, even with the best materials available, gives rise to large quantities of ionized gas which must be disposed of if the space between the contacts and other live parts in the arc chamber is to withstand the restored voltage of the circuit. From its inception the arc space must be conditioned progressively to withstand the increasing voltages imposed by the action of the interrupter on the arc. If the arc in moving from the contacts into the interrupter is envisioned in slow motion—keeping in mind the intense heat and ionization—it can be seen that at each point, the space which the arc

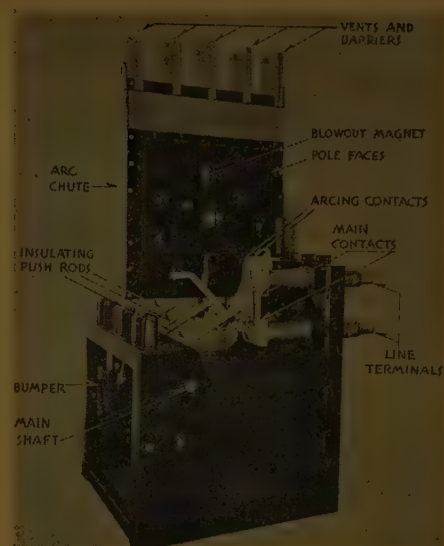


Figure 6. Three-pole 500,000-kva 7.5-kv magnetic deion air breaker showing one arc chute in position

has just vacated must be sufficiently deionized to withstand the voltage of the arc in the succeeding position. Otherwise, the arc will restrike to the earlier position, from which it must again be moved. Although it is difficult to avoid this restriking with perfection, excessive restriking causes proportionally greater ionization which must be disposed of for successful interruption of the circuit. Finally, the entire space between the live parts of the arc chamber, both internal and external, must withstand the restored voltage applied by the open circuit.

The interrupting element or arc chute of this breaker is arranged so that the arc is moved by a magnetic field into V-shaped slots in a multiplicity of refractory plates separated from each other. The planes of the plates are perpendicular to the arc stream. The arc chute is shown schematically in Figure 5. The lower part encloses the initial arc-drawing space and the space for extending the arc length for movement into the series of refractory deionizing plates.

A curved arc horn is located at each end of this lower part of the arc chute to provide rapidly separating arc terminal paths. Each arc horn is on the immediate upper periphery of a circular blowout coil. The coil above the stationary arcing contact is cut into series relationship with the arc as the arc impinges on the arc horn immediately above that coil. This adds sufficient magnetic field to that existing from the loop shape of the current path through the breaker to move the terminal of the arc on the movable arc tip rapidly onto the arc horn at the other end of the arc

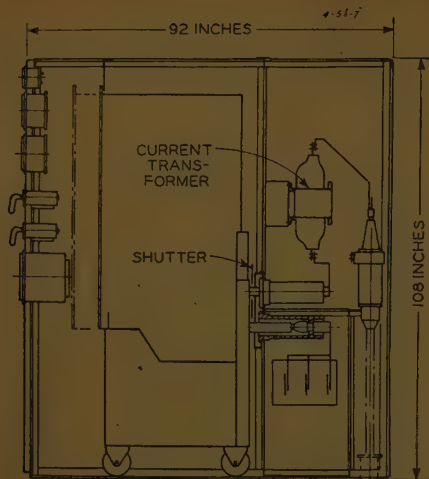


Figure 7. Dimensioned drawing showing 500,000-kva 7.5-kv magnetic deion air breaker in metal-clad switching equipment Type 75-DH-500 drawout unit 40 inches wide

chute and the corresponding blowout coil is introduced into the circuit. The magnetic field provided by the two blowout coils is applied to the arc space by suitably shaped pole faces, to move the arc as uniformly and as rapidly as possible consistent with the deionization of all of the space behind it. The deionization of this space between the contacts and arc horns is accomplished by venting the gases from the arc and cooling them to such an extent that breakdown will not occur. To this end the arc horns are vented freely, and the refractory plates above the arc horns are arranged in four groups spaced apart to provide five relatively wide vents evenly spaced.

The refractory plates are separated

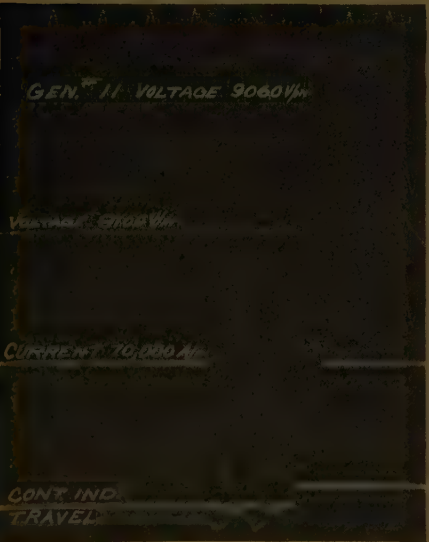


Figure 8. Oscillogram showing the interruption of 47,500 amperes at 5,900 volts at 60 cycles on a single pole of the 500,000-kva 7.5-kv magnetic deion air breaker

as much as possible for venting effect without sacrificing the deionization effect on the exhaust gases traveling from the ends of the V-shape slots to the ends of the plates. Lateral barriers are also placed at the end stack vent as an additional precaution against flashing over the entire end of the arc chamber.

In Figure 5, the arcing contacts are externally similar to those previously applied to magnetic deion breakers for 100,000, 150,000, and 250,000 kva³⁻⁶ but are equipped with heavier springs to prevent blowing open on the high currents involved. The arc tips and secondary contacts are made of silver tungsten. The main contacts are of the solid copper bridge type, faced with silver inlay and held in contact by strong compression springs. This construction provides for transferring the current from the main contacts to the arcing contacts, and the shape of the arcing contact parts accelerates the movement of the arc from the arc tips.

The three movable contact arms are operated by insulating push rods from a shaft running lengthwise across the front of the breaker. This shaft is operated through a toggle by a horizontally acting solenoid mechanism not shown. The shaft also has two arms coacting with bumpers to absorb the shock of opening.

Figure 6 shows the three-pole breaker with two arc chutes removed to show the contacts. A dimensional drawing of this breaker as part of a complete metal-clad switching equipment is shown in Figure 7.

Extensive high-power interrupting tests were made in the development of the breaker. Figure 8 shows an oscillogram of an opening test on the completed breaker of 47,500 amperes at 5,900 volts, 60 cycles on a single pole. Figure 9 shows a close-open test of 45,700 am-

Table I. Single-Phase Interrupting Tests
7,500-Volt 500,000-Kva Steel-Mill Circuit Breaker

Test Number	Generator Voltage	Rms Amperes Interrupted	Arcing Time (Cycles)	Interrupting Time (Cycles)
Opening Tests 60 Cycles				
1...	3,500	11,000	1.50	2.75
2...	5,900	11,900	1.20	2.60
3...	5,950	21,400	1.00	2.40
4...	5,900	34,800	1.00	2.40
5...	3,500	11,400	1.00	2.50
6...	5,900	30,500	0.80	2.30
7...	5,900	29,200	0.90	2.30
8...	5,900	21,000	0.80	2.20
9...	5,900	46,550	0.80	2.20
10...	5,900	47,250	1.10	2.60
11...	5,900	47,250	0.75	2.30
12...	5,900	46,950	1.25	2.60
Opening Tests 25 Cycles				
13...	5,850	5,225	0.50	1.00
14...	5,850	21,850	0.45	0.90
15...	3,500	20,250	0.45	0.95
16...	6,100	29,200	0.40	1.20
17...	6,100	43,700	0.50	1.00
18...	6,150	42,800	0.40	0.90
Close-Open Tests 25 Cycles				
19...	6,100	1,415	1.20	1.70
20...	6,100	42,900	0.40	0.90
21...	6,100	45,700	0.60	1.20

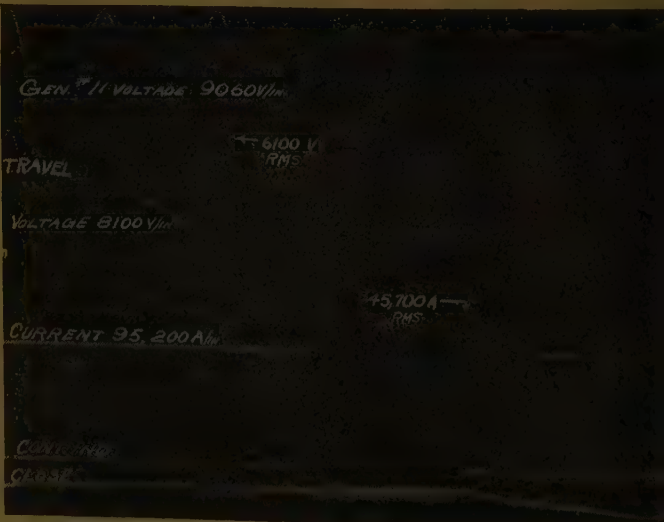
peres at 6,100 volts, 25 cycles on a single pole.

Table I shows three series of tests on a single pole of the breaker, all of which were made without maintenance. Of the 21 tests, 8 are at more than 40,000 amperes and 16 are at more than 20,000 amperes. This performance is equivalent to years of actual service. Proof of satisfactory performance over the entire range of lower currents was obtained by subjecting the breaker, without any form of maintenance, to a series of approximately 100 interrupting tests.

Conclusion

The principle of magnetic diffusion has been applied to a complete line of circuit breakers with interrupting capacities

Figure 9. Oscillogram similar to Figure 9 except showing a single-phase close-open interruption of 45,700 amperes with a generator voltage of 6,100 and at 25 cycles



The Asymmetrical Stator as a Means of Starting Single-Phase Induction Motors

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THE shaded-pole motor is quite simple to construct; but for all but the smallest sizes, losses are large; and if distributed windings are used, its construction becomes more complicated. A single-phase induction motor may be given starting torque by varying the rotor constants over the pole face, either by asymmetrical iron structure or winding. Starting torque is comparable with that of a shaded-pole motor, and construction is very simple with nothing to get out of order. The chief drawback appears to be the smaller power factor which is due to reduced mutual inductance.

Means of Securing an Asymmetrical Stator

Starting torque arises from two sources:

1. The difference in leakage inductance of the rotor bars on one side of the pole from that on the other causes a different current to flow on each side, producing a resultant torque, as in a repulsion motor.
2. The difference in mutual reactance on the two sides of the poles gives the rotor current under the two sides some difference in phase, which also produces a resultant torque.

One means of securing these differences is to wind more turns about one side of the

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ranging from 50,000 kva⁶ at 2,500 volts to the 500,000-kva 7.5-kv breaker described in this paper. Laboratory tests show that this most recent breaker is well suited to the operating conditions of steel mill and equivalent service and that it has ample short-circuit interrupting capacity for use in large power concentrations at 6,600 or 6,900 volts.

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pole face, which we will designate as a , than about the other side, designated b , thus causing a difference in the permeability of both the rotor and stator iron. If the iron at b has the maximum perme-

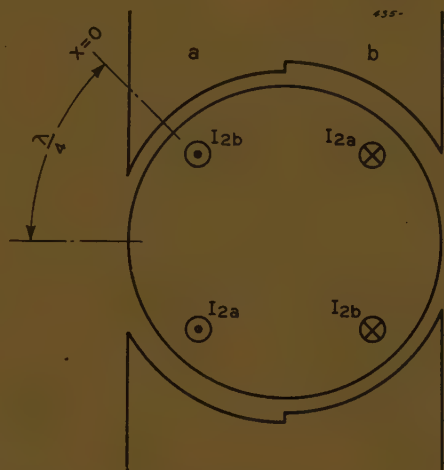


Figure 1. Relative position of fluxes and currents

ability, the flux density at a will be above that of maximum permeability; the rotor bars under b will have greater inductance than those under a , and since the current through these encircles a , the component of rotor leakage reactance X_{2a} will be greater than X_{2b} . For a lower voltage and flux density, the opposite will be the case; hence, we have the interesting possibility of the starting direction being reversed by a change in starting voltage. In order to utilize this effect fully, the rotor bars should be surrounded

completely by iron. It is quite difficult to calculate the rotor reactance of this type of motor; thus, it is hard to design efficiently.

The case of varying the air gap over the pole face is easier to calculate. These formulas are derived in the appendix. While the greatest difference in both rotor inductance and mutual reactance occurs when the air gap has its maximum value over half the pole face, changing abruptly to a minimum, harmonic reactances of the rotor are least when the so-called zigzag reactance, that is, leakage reactance of the rotor bars due to flux crossing the air gap, varies sinusoidally over each pole. If it is assumed that this reactance is to be inversely proportional to the air gap, this requires that

$$1/\Delta = aA + 2A \cos 2\pi x/\lambda \quad (1)$$

where

Δ = air gap (all dimensions in this paper are given in inches)

$$aA = (1/2)(1/\Delta_{\min} + 1/\Delta_{\max})$$

$$2A = (1/2)(1/\Delta_{\min} - 1/\Delta_{\max})$$

x = co-ordinate measured along rotor periphery

λ = pole pitch

It might seem desirable to create a sinusoidal flux wave by increasing the turns about each stator tooth in proportion to the increase in air gap under that tooth. This introduces harmonics into the magnetomotive-force wave which gives a greater harmonic content to the mutual reactance than an ordinary sinusoidally distributed winding would give.

Difference in flux density over a and b may cause difference in rotor permeability, which may increase or decrease the resultant torque; but unless the rotor bars are surrounded completely by iron, this effect should be small. Difference in flux density over a and b also may produce a difference in hysteresis angle of advance between flux a and b , producing a rotating field; but this effect is also quite small under ordinary conditions.

Computation of Rotor Currents and Torque

P. H. Trickey¹ has given an analysis of the shaded-pole motor which forms the basis of this development. The space distribution waves of field flux and rotor current are resolved into Fourier series. Each harmonic is divided into two components or phases 90 degrees apart, denoted by subscripts a and b . In Appendix II the values of these components are calculated. Figure 1 shows the relative position of the fields and currents for the

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fundamental flux wave; Figure 2 shows the equivalent circuit diagram. If we add voltages about the shunt circuits a and b associated with the n th harmonic, we get

$$({}_nR_{2a} + j {}_nX_{2a}) {}_nI_{2a} = (I - {}_nI_{2a}) j {}_nX_a + {}_nS(I - {}_nI_{2b}) {}_nX_b - {}_nS {}_nI_{2b} {}_nX_{2b} \quad (2)$$

$$({}_nR_{2b} + j {}_nX_{2b}) {}_nI_{2b} = (I - {}_nI_{2b}) j {}_nX_b - {}_nS(I - {}_nI_{2a}) {}_nX_a + {}_nS {}_nI_{2a} {}_nX_{2a} \quad (3)$$

where

${}_nR_{2a}$ = rotor resistance to n th space harmonic of current, phase a

(All impedances mentioned in body of paper are referred to primary.)

${}_nX_{2a}$ = rotor leakage reactance, n th harmonic, phase a

${}_nX_a$ = mutual reactance, n th harmonic, phase a

${}_nI_{2a}$ = rotor current, n th harmonic, phase a

(Similar quantities of phase b have subscript b .)

n = order of harmonic

S = ratio of rotor speed to synchronous speed, positive in direction of increasing x

Ordinarily the fundamental flux, $n=1$, is all that need be considered; but with a salient pole the third harmonic is apt to affect the torque appreciably. The equivalent resistance, R_h , due to iron loss, should be included as shown, but its computation is outside the province of this paper, its chief effect being to increase the inphase component of current.

If equations 2 and 3 are solved simultaneously for ${}_nI_{2a}$ and ${}_nI_{2b}$

$${}_nI_{2a} = {}_nK_a I \quad {}_nI_{2b} = {}_nK_b I \quad (4)$$

$${}_nK_a = {}_nF_a / {}_nF \quad {}_nK_b = {}_nF_b / {}_nF \quad (5)$$

$${}_nF_a = {}_nS {}_nR_{2b} {}_nX_b - (1 - n^2 S^2) {}_nX_{ob} {}_nX_a + j {}_nR_{2b} {}_nX_a \quad (6)$$

$${}_nF_b = -{}_nS {}_nR_{2a} {}_nX_a - (1 - n^2 S^2) {}_nX_{oa} {}_nX_b + j {}_nR_{2a} {}_nX_b \quad (7)$$

$${}_nF = {}_nR_{2a} {}_nR_{2b} - (1 - n^2 S^2) {}_nX_{oa} {}_nX_{ob} + j ({}_nR_{2a} {}_nX_{ob} + {}_nR_{2b} {}_nX_{oa}) \quad (8)$$

where

${}_nX_{oa} = {}_nX_a + {}_nX_{2a}$ and so forth.

In the primary circuit

$$I(R_1 + jX_1) + (I - {}_nI_{2a}) j {}_nX_a + (I - {}_nI_{2b}) j {}_nX_b + (I - {}_nI_{2a}) j {}_nX_a + (I - {}_nI_{2b}) j {}_nX_b = E$$

where

R_1 = primary resistance

X_1 = total primary leakage reactance, excluding ${}_nX_a$ and ${}_nX_b$

E = voltage

If the values of ${}_nI_{2a}$ and so forth are put in from equation 4

$$I[R_1 + j(X_1 + X_1') - {}_nK_a j {}_nX_a - {}_nK_b j {}_nX_b - {}_nK_a j {}_nX_a - {}_nK_b j {}_nX_b] = E \quad (9)$$

where

X_1 = total mutual reactance

X_1' = primary leakage reactance, excluding harmonic and skew reactance

Torque in ounce inches for the n th harmonic is given by the real part of

$$n^T = 11.3(nP/f) [(n t_b / n t_a) {}_nX_a (I - {}_nI_{2a}) \times \text{conj } {}_nI_{2b} - (n t_a / n t_b) {}_nX_b (I - {}_nI_{2b}) \times \text{conj } {}_nI_{2a}] \quad (10)$$

where

P = number of poles

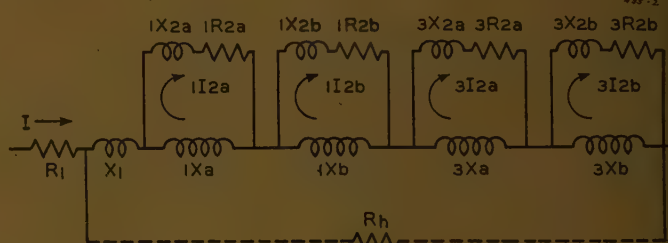
f = frequency

$n t_a$ = turns per pole effective for n th harmonic, phase a

Let us put this formula into a form more suitable for computation. Now ${}_nK_a$ and ${}_nK_b$ are complex, and so we may put them in the form

$${}_nK_a = {}_nU + j {}_nU \quad {}_nK_b = {}_nV + j {}_nV$$

Figure 2. Equivalent circuit diagram of asymmetrical field induction motor



If we substitute these expressions in equation 4, we find that the real part of

$$(I - {}_nI_{2a}) \text{ conj } {}_nI_{2b} = I^2 (1 - {}_nU - j {}_nU) ({}_nV - j {}_nV) = I^2 [{}_nV - ({}_nU {}_nV + {}_nU {}_nV)]$$

$$(I - {}_nI_{2b}) \text{ conj } {}_nI_{2a} = I^2 (1 - {}_nV - j {}_nV) ({}_nU - j {}_nU) = I^2 [{}_nU - ({}_nU {}_nV + {}_nU {}_nV)]$$

so that

$$n^T = 11.3(nPI^2/f) [(n t_b / n t_a) {}_nX_a [{}_nV - ({}_nU {}_nV + {}_nU {}_nV)] - (n t_a / n t_b) {}_nX_b [{}_nU - ({}_nU {}_nV + {}_nU {}_nV)]] \quad (11)$$

Standstill Conditions

When $S=0$, the system of equations 4 to 8 reduces to

$${}_nK_a = j {}_nX_a / ({}_nR_{2a} + j {}_nX_{oa}) = ({}_nK_{ra} / {}_nX_a) ({}_nX_{oa} + j {}_nR_{2a}) \quad (12)$$

where

$${}_nK_{ra} = ({}_nX_a / {}_nX_{oa})^2 / [1 + ({}_nR_{2a} / {}_nX_{oa})^2]$$

with a similar formula for b .

When $t_a = t_b$ and $R_{2a} = R_{2b} = R_2/2$ (R_2 being the complete fundamental rotor resist-

ance as calculated by usual methods), as is often the case, equation 12 becomes, for $n=1$

$$1^T = 11.3(P {}_1K_{ra} {}_1K_{rb} / {}_1X_a {}_1X_b f) I^2 \times [({}_1X_{2b} - {}_1X_{2a}) ({}_1R_2^2 - {}_1X_{oa} {}_1X_{ob}) - 2 {}_1R_2^2 ({}_1X_a - {}_1X_b)] \quad (13)$$

showing that the torque depends on both ${}_1X_{2b} - {}_1X_{2a}$ and ${}_1X_a - {}_1X_b$. Since we may put ${}_1R_{2a} = R_2' t_a^2$ and ${}_1X_{2a} = X_{2a}' t_a^2$, and so forth, it becomes evident on putting these values in equation 11 for $S=0$, that starting torque is independent of any difference in t_a and t_b , except as they affect the permeability.

Motor Constants With Sinusoidal Permeance

With an ordinary symmetrical winding, $t_a = t_b = t_p / \sqrt{2}$ and $R_{2a} = R_{2b} = R_2/2$, where t_p is the effective turns per pole calculated in the usual manner.

With the air gap of equation 1, and with any type of winding

$$R_{2a} = 8(P t_a)^2 [(\sqrt{W^2 + S k^2} / S_s S_c) + (0.637 D_r K_r / S_r P^2)] \rho \quad (14)$$

where we have dropped the subscript for harmonics as we are going to deal with the fundamental only, and

S_s = number of rotor slots

S_c = cross section of rotor bar

$S k$ = skew in inches

S_r = cross section of end ring

W = axial width of rotor

ρ = resistivity

D_r = diameter of end ring

K_r = ring constant (see reference 2)

For R_{2b} use t_b instead of t_a

$$X_{2a} = X_{sa} + X_{ska} + (X_{2a \max} + X_{2a \min})/2 - (X_{2a \max} - X_{2a \min})/4 \quad (15)$$

$$X_{2b} = X_{sb} + X_{skb} + (X_{2b \max} + X_{2b \min})/2 + (X_{2b \max} - X_{2b \min})/4 \quad (16)$$

$$X_{sa} = \text{rotor slot reactance, phase } a = 2\pi f(P t_a)^2 10^{-9} 25.52 (W K_s / S_s) \quad (17)$$

K_s = rotor slot constant (see reference 1)

For X_{sb} use t_b

$$X_{2a \max} = 2\pi f(P t_a)^2 10^{-9} 25.52 (W T_f / S_s^4 \Delta_{\min}) \quad (18)$$

T_f = rotor tooth face in inches

For $X_{2a \min}$ use $\Delta_{\max}$, for $X_{2b \min}$ use l_b and $\Delta_{\max}$, and so forth. The preceding formula applies only when there are no stator slots to break the magnetic circuit, and when the rotor bars are not completely surrounded by iron

$$\begin{aligned} X_{2ka} &= (1 - C_{sk}) X_a' \\ X_{2kb} &= (1 - C_{sk}) X_b' \end{aligned} \quad (19)$$

$$C_{sk} = \sin(\pi Sk/2\lambda)/(\pi Sk/2\lambda) \quad (20)$$

$$\begin{aligned} \text{Since } \sin x &= x - x^3/6 \text{ for small values of } x \\ 1 - C_{sk} &= (1/6)(\pi Sk/2\lambda)^2 \end{aligned} \quad (21)$$

approximately for small values of Sk/λ .

$$\begin{aligned} \text{Thus} \\ X_{2a} - X_{2a'} &= (X_{2a \max} - X_{2a \min})/2 - \\ &\quad (X_a - X_b)(1 - C_{sk}) \quad (22) \end{aligned}$$

If equation 22 is substituted in equation 13, the term in brackets becomes

$$\begin{aligned} (R_2^2 - X_{oa} X_{ob})(X_{2a \max} - X_{2a \min})/2 - \\ (X_a - X_b)[(R_2^2 - X_{oa} X_{ob})(1 - C_{sk}) + 2R_2^2] \end{aligned} \quad (23)$$

Thus the effect of zigzag reactance is opposed to that of skew. When R_2 is small, it may be desirable to reduce X_{2a} and X_{2b} as much as possible, depending on $X_{2ka} - X_{2kb}$ for starting torque by increasing the skew an integral number of slots. When $2R_2$ is greater than $(R_2^2 - X_{oa} X_{ob})(1 - C_{sk})$, it may be desirable to reduce the skew as much as possible. Since, in all practical cases, R_2^2 is less than $X_{oa} X_{ob}$, torque from zigzag reactance in this case is in the same direction as that due $X_a - X_b$. The increase of R_2 increases the torque per ampere (until it approaches the magnitude of X_{ob}), though it reduces the current; however, increase of R_2 increases the slip and losses and decreases the power factor, as in any induction motor. Since $X_a - X_b$ and $X_{2b} - X_{2a}$ usually must be increased by reducing X_b , the starting torque is limited by the decrease in power factor and increase in rotor losses permissible.

Appendix I. Equivalent Impedance of Squirrel-Cage Rotor

Let there be an infinite number of rotor bars having the same impedance for an inch of periphery as the actual rotor. Figure 3 represents an elementary circuit about the rotor. AB and DC are the endrings, AD being the bar where the ring current $I_r = 0$. Then at x

$$I_r = \int_c^x J dx$$

where J = current density in bars per inch of periphery.

The voltage drop E_r in each ring from x to d is

$$E_r = R_r \int_x^d I_r dx = R_r \int_x^d dx \int_c^x J dx$$

where R_r = resistance per inch of end ring. Let the voltage induced at x be $E(x)$ and that, at a fixed point, d be $E(d)$. Then the voltage about the whole circuit is

$$\begin{aligned} J dx (Z_1/dx) + 2R_r \int_x^d dx \int_c^x J dx = \\ E(x) - E(d) \quad (24) \end{aligned}$$

where

$$\begin{aligned} Z_1 &= Z_B \lambda P / S_s = \text{impedance of one inch of bars at } x \\ Z_B &= \text{actual impedance of one bar} \end{aligned} \quad (25)$$

If we differentiate twice, and remember that $E(d)$ is constant

$$(d^2/dx^2)(JZ_1) + 2R_r J = d^2E/dx^2 \quad (26)$$

We may represent J , E , and Z_1 in a Fourier series in which

$$\begin{aligned} \theta &= \pi x/\lambda \\ J &= J_a \sin \theta + J_b \sin 3\theta + \dots + \\ &\quad J_b \cos \theta + J_b \cos 3\theta + \dots \end{aligned} \quad (27)$$

$$\begin{aligned} E &= E_a \sin \theta + E_b \sin 3\theta + \dots + \\ &\quad E_b \cos \theta + E_b \cos 3\theta + \dots \end{aligned} \quad (28)$$

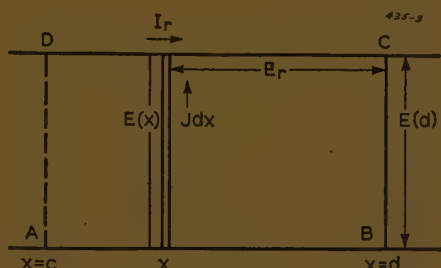


Figure 3. Rotor circuit diagram

$$\begin{aligned} Z_1 &= Z_c + Z_c \sin 2\theta + Z_c \sin 4\theta + \dots + \\ &\quad Z_d + Z_d \cos 2\theta + \dots \end{aligned} \quad (29)$$

Z_1 has a period of 2θ because it repeats at every pole. In order to solve the differential equation 26, it is necessary only to substitute in it equations 27, 28, and 29. Now, if we put equations 27 and 29 in more concise form

$$\begin{aligned} JZ_1 &= \left(\sum_q J_a \sin q\theta + \sum_q J_b \cos q\theta \right) \times \\ &\quad \left(\sum_p C \sin p\theta + \sum_p D \cos p\theta \right) \end{aligned} \quad (30)$$

If we use product formulas of the type

$$\begin{aligned} \sin m\theta \sin n\theta &= -(1/2) \cos(m+n)\theta + \\ &\quad (1/2) \cos(m-n)\theta \end{aligned}$$

we find, by expanding equation 30

$$\begin{aligned} JZ_1 &= (1/2) \sum_p \sum_q C J_a [-\cos(p+q)\theta + \\ &\quad \cos(p-q)\theta] + (1/2) \sum_p \sum_q C J_b [\sin(p+q)\theta + \\ &\quad \sin(p-q)\theta] + (1/2) \sum_p \sum_q D J_a \times \\ &\quad [\sin(p+q)\theta - \sin(p-q)\theta] + \\ &\quad (1/2) \sum_p \sum_q D J_b [\cos(p+q)\theta + \\ &\quad \cos(p-q)\theta] \end{aligned} \quad (31)$$

where the summation extends over all the positive values of p and q for which D and

C exist. Pick out the coefficient of $\sin n\theta$ in $pCJ_b \sin(p+q)\theta$, where $n=p+q$; it is

$$\sum_q n-qCJ_b$$

Likewise, in the term $pCJ_b \sin(p-q)\theta$, the coefficient of $\sin n\theta$, where $n=p-q$, is

$$\sum_q n-qCJ_b - \sum_q n-qCJ_b$$

for when $q > p$, n is negative, and the terms are of the form

$$q-|n|CJ_b \sin(-|n|\theta) = -q-|n|CJ_b \sin|n|\theta$$

where $|n|=q-p$. If we pick out the other coefficients in the same way

$$\begin{aligned} Z_1 J &= (1/2) \sum_n M_a \sin n\theta + \\ &\quad (1/2) \sum_n M_b \cos n\theta \end{aligned} \quad (32)$$

where

$$\begin{aligned} nM_a &= \sum_q n-qCJ_b - \sum_q n-qCJ_b + \\ &\quad \sum_q n+qCJ_b + \sum_q n-qD J_a + \sum_q n-qD J_a - \\ &\quad \sum_q n+qD J_a \end{aligned} \quad (33)$$

$$\begin{aligned} nM_b &= -\sum_q n-qCJ_a + \sum_q n-qCJ_a + \\ &\quad \sum_q n+qCJ_a + \sum_q n-qD J_b + \\ &\quad \sum_q n-qD J_b + \sum_q n+qD J_b \end{aligned} \quad (34)$$

As before, the summation extends over all positive values of q for which the factors C and D exist.

We are ready now to substitute the value of JZ_1 , that is, equation 32, in equation 26

$$\begin{aligned} -\sum(n^2\pi^2/2\lambda^2)nM_a \sin n\pi x/\lambda - \\ \sum(n^2\pi^2/2\lambda^2)nM_b \cos n\pi x/\lambda - \\ 2R_r \sum_n J_a \sin n\pi x/\lambda - \\ 2R_r \sum_n J_b \cos n\pi x/\lambda \\ = -(\pi^2/\lambda^2) [\sum_n n^2 E_a \sin n\pi x/\lambda - \\ \sum_n n^2 E_b \cos n\pi x/\lambda] \end{aligned} \quad (35)$$

We may separate equation 35 in a different equation for each harmonic

$$\begin{aligned} [(1/2)nM_a + 2\lambda^2 R_r n J_a / n^2 \pi^2 \sin(n\pi x/\lambda)] \\ = nE_a \sin(n\pi x/\lambda) \end{aligned} \quad (36)$$

$$\begin{aligned} [(1/2)nM_b + 2\lambda^2 R_r n J_b / n^2 \pi^2 \cos(n\pi x/\lambda)] \\ = nE_b \cos(n\pi x/\lambda) \end{aligned} \quad (37)$$

Let us now confine our attention to the case in which all orders of C are zero. Then each value of nM_a is made up of terms including nJ_a , and we get the system of equations in J_a of the form

$$\begin{aligned} (11Z_a' J_a + 13Z_a' J_a + 15Z_a' J_a + \dots) \times \\ \sin \pi x/\lambda E_a \sin \pi x/\lambda \\ (31Z_a' J_a + 33Z_a' J_a + 35Z_a' J_a + \dots) \times \\ \sin 3\pi x/\lambda E_a \sin 3\pi x/\lambda \end{aligned} \quad (38)$$

$$\left(\sum_m n m Z_a' J_a \right) \sin(n\pi x/\lambda) = nE_a \times \sin(n\pi x/\lambda)$$

If we multiply by $nJ_a \sin(n\pi x/\lambda) dx$, the element of current at x , gives $d_n W$, the element of rotor losses + reactive power for the n th harmonic. Integrating over the whole rotor

$$P \int_0^\lambda \sum_{nm} Z'_{am} J_a \sin^2(n\pi x/\lambda) dx = nW \quad (39)$$

$$(P\lambda/2) n J_a \sum_{nm} Z'_{am} J_a = nW$$

Now the total current that encircles x of the m th harmonic is

$$mJ_a \int \sin(m\pi x/\lambda) dx$$

Since this flows through one turn, it is also the magnetomotive force of the secondary

$$MMF_2 = (\lambda m J_a / \pi m) \cos(m\pi x/\lambda) \quad (40)$$

The magnetomotive force of the primary is $(4/\pi) m^2 J_a \cos(m\pi x/\lambda)$. Equating primary and secondary magnetomotive force

$$mJ_a = (4m/\lambda) m^2 J_a \quad (41)$$

Substitution in equation 39 gives

$$nW = (8P/\lambda) n^2 J_a \sum_{nm} m^2 J_a Z'_{am} \quad (42)$$

Thus nW has the form

$$n_1 Z_a n_1 J_a + n_2 Z_a n_2 J_a + \dots$$

and if corresponding products of J_a are equated to those of J_a

$$nmZ_a = (8P/\lambda) n^2 m^2 J_a Z'_{am} \quad (43)$$

where the D 's that make up nmZ'_a are given in terms of one inch of rotor periphery. Since, in equation 25

$$Z_1 = Z_B \lambda P / S_c$$

$$nmZ'_a = nmZ'_a \lambda P / S_c$$

and

$$nmZ_a = (8P^2/S_c) n^2 m^2 J_a Z'_a \quad (44)$$

where nmZ'_a is given in terms of impedance per bar. The formula for phase b is obtained, as usual, by substituting quantities in b in place of those with subscript a . Thus, we have the system of equations giving the rotor voltage in terms of the harmonic currents, all referred to the stator

$$11Z_a 1I_a + 12Z_a 2I_a + 13Z_a 3I_a + \dots = 1E_a$$

$$21Z_a 1I_a + 22Z_a 2I_a + 23Z_a 3I_a + \dots = 2E_a \quad (45)$$

The impedances of form nmZ can be neglected usually, in which case equation 45 becomes the equations we used in the body of the paper, equations 2 and 3.

As the simplest example, let $Z_1 = 0D + 2D \cos 2\pi x/\lambda$ which is the impedance given by the air gap represented in equation 1. If we expand nM_a from equation 33 and nM_b from equation 34

$$1M_a = (2_0D - 2_2D) 1J_a + 2_2D 3J_a$$

$$2M_a = 2_2D 1J_a + 2_0D 3J_a + 2_2D 5J_a$$

$$3M_a = 2_2D 3J_a + 2_0D 5J_a + 2_2D 7J_a$$

$$1M_b = (2_0D + 2_2D) 1J_b + 2_2D 3J_b$$

$$2M_b = 2_2D 1J_b + 2_0D 3J_b + 2_2D 5J_b$$

$$3M_b = 2_2D 3J_b + 2_0D 5J_b + 2_2D 7J_b$$

If we put these values in equation 36

$$(1/2)(2_0D - 2_2D + K') 1J_a + 2_2D 3J_a = 1E_a$$

$$(1/2) 2_2D 1J_a + (2_0D + K'/9) 3J_a + 2_2D 5J_a = 3E_a$$

$$(1/2) 2_2D 3J_a + (2_0D + K'/25) 5J_a + 2_2D 7J_a = 5E_a \quad (46)$$

There are similar equations for b , except that all signs are positive.

Comparing with equation 38, we see that the coefficient of mJ_a is identical with nmZ . If we desire to express the D 's in terms of impedance per bar, as in equation 44, we shall have to multiply K' by $S_c/P\lambda$.

$$K = (4R_r \lambda^2 / \pi^2) (S_c / \lambda P) = 4R_r \lambda S_c / \pi^2 P$$

$$= 4R_r D_r S_c / P^2 \pi \quad (47)$$

where D_r = diameter of ring at ends of conductors. From equations 44 and 46 we find, putting

$$nmG_a = (4P^2/S_c) n^2 m^2 J_a \quad (48)$$

$$11Z_a = 11G_a (2_0D - 2_2D + K)$$

$$12Z_a = 12G_a 2D$$

$$13Z_a = 0$$

$$21Z_a = 21G_a 2D$$

$$22Z_a = 22G_a (2_0D + K/9)$$

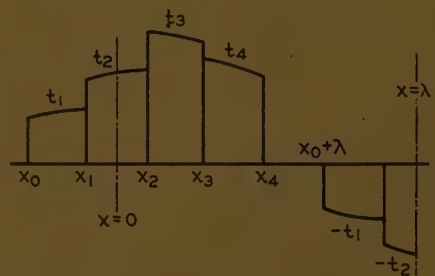


Figure 4. Diagram illustrating notation of stator teeth

$$31Z_a = 31G_a 2D$$

$$32Z_a = 0$$

$$33Z_a = 33G_a 2D$$

$$34Z_a = 34G_a (2_0D + K/25) \quad (49)$$

In a similar manner we find

$$nmG_b = (4P^2/S_c) n^2 m^2 J_b \quad (50)$$

$$11Z_b = 11G_b (2_0D + 2_2D + K) \quad (51)$$

All the other Z 's are obtained from equation 49 by using G_b instead of G_a .

Computing Bar Constants

The resistance per bar is given by

$$R_B = \rho \sqrt{W^2 + Sk^2} / S_c \quad (51a)$$

where

ρ = resistivity in ohms per inch cube
 W = length of rotor
 Sk = skew in inches
 S_c = section of conductor

The ring resistance per inch is

$$nR_r = \rho nK_r / S_r \quad (52)$$

where

S_r = section of ring
 nK_r = Trickey's ring constant²
 $= (nP/2)(1 - ID/D_r)[1 + (ID/D_r)^{Pn}] \div [1 - (ID/D_r)^{Pn}]$

The leakage reactance is divided into three components:

1. SLOT REACTANCE

$$X_s = 2\pi f 3.19 \times 10^{-8} WK_s$$

where

$$K_s = \text{rotor slot constant}^1 \quad (53)$$

2. ZIGZAG REACTANCE

$$X_z = 2\pi f 3.19 \times 10^{-8} WT_f / 4 \Delta$$

where

$$T_f = \text{tooth face in inches} \quad (54)$$

If the stator slots break the magnetic circuit about the rotor bars, X_z probably will be smaller. Let

$$1/\Delta = 0A + 2A \cos 2\pi x/\lambda + 4A \cos 4\pi x/\lambda + \dots$$

Then

$$0D = R_B + j(X_s + 2\pi f 3.19 \times 10^{-8} WT_f 0A/4) \quad (55)$$

$$2D = j 2\pi f 3.19 \times 10^{-8} WT_f 2A/4 \text{ and so forth} \quad (56)$$

3. SKEW REACTANCE

$$nX_{ska} = n^2 X_a (1 - nC_{sk})$$

$$nX_{skb} = n^2 X_b (1 - nC_{sk})$$

$$nC_{sk} = [\sin(n\pi Sk/2\lambda)] / (n\pi Sk/2\lambda) \quad (57)$$

nX_{ska} is to be added to the value of nmZ_a given in equation 49, and nX_{skb} is to be added to nmZ_b in equation 51.

Appendix II. Air-Gap Reactance

Figure 4 represents the flux wave.

Let

t_m = turns about stator tooth m
 $p = 0.4\pi 2.54 A_e / \Delta = 3.19 A_e / \Delta$
 A_e = effective area per square inch of pole face

Total Reactance

$$\phi_m = WI \int_{x_{m-1}}^{x_m} t_m p dx$$

$$= \text{flux through } m\text{th tooth} \quad (58)$$

$$E_m = 2\pi f 10^{-8} t_m WI \int_{x_{m-1}}^{x_m} t_m p dx$$

$$= \text{voltage induced in winding about } m\text{th tooth}$$

$$X_t = (P/I) E_m = 2\pi f 10^{-8} PW \sum t_m^2 \int_{x_{m-1}}^{x_m} p dx$$

$$= \text{total reactance linking primary and secondary} \quad (59)$$

If $p = 0p + 2p \cos 2\pi x/\lambda$

$$X_t = 2\pi f 10^{-8} PW \sum t_m^2 \left[\int_{x_{m-1}}^{x_m} 0p dx + \int_{x_{m-1}}^{x_m} 2p \cos(2\pi x/\lambda) dx \right]$$

$$X_t = 2\pi f 10^{-8} PW \sum t_m^2 [0.5\phi(x_m - x_{m-1}) + (2\phi\lambda/2\pi)(\sin 2\pi x_m/\lambda - \sin 2\pi x_{m-1}/\lambda)] \quad (60)$$

$$X_t = 2\pi f 10^{-8} PW \sum t_m^2 [0.5\phi(x_m - x_{m-1}) + (2\phi\lambda/\pi) \cos \pi(x_m + x_{m-1})/\lambda \times \sin \pi(x_m - x_{m-1})/\lambda] \quad (61)$$

Harmonic Reactance

$nB_a = nB_{a \max} \cos n\pi x/\lambda$ = cosine component n th harmonic flux density

From the formula for Fourier coefficients, we find

$$nB_{a \max} = (4/\pi)I_n a = (2/\pi) \times \sum \int_{x_{m-1}}^{x_m} I_m \phi \cos(n\pi x/\lambda) d(\pi x/\lambda) \quad (62)$$

Let

$$\phi = \phi_1 + \phi_2 \cos 2\pi x/\lambda$$

$$n_a = (1/2) \sum \int_{x_{m-1}}^{x_m} \phi \cos(n\pi x/\lambda) d(\pi x/\lambda) + (1/2) \sum \int_{x_{m-1}}^{x_m} 2\phi \cos(2\pi x/\lambda) \cos(n\pi x/\lambda) \times d(\pi x/\lambda)$$

$$n_a = (\phi/2n) \sum t_m (\sin n\pi x_m/\lambda - \sin n\pi x_{m-1}/\lambda) + [2\phi/4(n+2) \times \sum t_m (\sin(n+2)\pi x_m/\lambda - \sin(n+2)\pi x_{m-1}/\lambda) + [2\phi/4(n-2) \times \sum t_m (\sin(n-2)\pi x_m/\lambda - \sin(n-2)\pi x_{m-1}/\lambda)] \quad (63)$$

$$n_a = (\phi/2n) \sum t_m \cos [n\pi(x_m + x_{m-1})/2\lambda] \sin [n\pi(x_m - x_{m-1})/2\lambda] + [2\phi/2(n+2) \times \sum t_m \cos [(n+2)\pi(x_m + x_{m-1})/2\lambda] \sin [(n+2)\pi(x_m - x_{m-1})/2\lambda] + [2\phi/2(n-2) \times \sum t_m \cos [(n-2)\pi(x_m + x_{m-1})/2\lambda] \sin [(n-2)\pi(x_m - x_{m-1})/2\lambda]] \quad (64)$$

Likewise

$nB_b = nB_{b \max} \sin n\pi x/\lambda$ = sin component, n th harmonic flux density

$$nB_{b \max} = (4/\pi)I_n b = (2/\pi) \sum \int_{x_{m-1}}^{x_m} I_m \phi \sin(n\pi x/\lambda) d(\pi x/\lambda)$$

With aforesaid permeance, we find, as before

$$n_b = (\phi/2n) \sum t_m (\cos n\pi x_{m-1}/\lambda - \cos n\pi x_m/\lambda) + [2\phi/4(n+2) \times \sum t_m (\cos(n+2)\pi x_{m-1}/\lambda - \cos(n+2)\pi x_m/\lambda) + [2\phi/4(n-2) \times \sum t_m (\cos(n-2)\pi x_{m-1}/\lambda - \cos(n-2)\pi x_m/\lambda)] \quad (65)$$

$$n_b = (\phi/2n) \sum t_m \sin [n\pi(x_m + x_{m-1})/2\lambda] \sin [n\pi(x_m - x_{m-1})/2\lambda] + [2\phi/2(n+2) \times \sum t_m \sin [(n+2)\pi(x_m + x_{m-1})/2\lambda] \sin [(n+2)\pi(x_m - x_{m-1})/2\lambda] + [2\phi/2(n-2) \times \sum t_m \sin [(n-2)\pi(x_m + x_{m-1})/2\lambda] \sin [(n-2)\pi(x_m - x_{m-1})/2\lambda]] \quad (66)$$

Let $n\phi_{am}$ = cosine component of flux through m th tooth, n th harmonic.

$$n\phi_{am} = W \int_{x_{m-1}}^{x_m} nB_a dx = W \int_{x_{m-1}}^{x_m} (4/\pi)I_n a \times \cos(n\pi x/\lambda) dx$$

$$nX_{am} = (2\pi f 10^{-8}/I) t_m n\phi_{am} = \text{reactance of } m\text{th tooth, } n\text{th harmonic, phase } a = 2\pi f 10^{-8} (4/\pi^2) W \lambda n a (t_m/n) \times (\sin n\pi x_m/\lambda - \sin n\pi x_{m-1}/\lambda)$$

Summing up the reactance for all the teeth, we have

$$nX'_a = 2\pi f 10^{-8} (8/\pi^2) PW \lambda n a n t_a \quad (67)$$

where

nX'_a = total mutual reactance, n th harmonic, phase a . The accent indicates that skew has not been deducted.

$$n t_a = (1/2n) \sum t_m (\sin n\pi x_m/\lambda - \sin n\pi x_{m-1}/\lambda) = (1/n) \sum t_m \cos [n\pi(x_m + x_{m-1})/2\lambda] \times \sin [n\pi(x_m - x_{m-1})/2\lambda] = n\text{th harmonic of effective turns per pole, phase } a \quad (68)$$

Likewise it can be shown that

$$nX'_b = 2\pi f 10^{-8} (8/\pi^2) PW \lambda n b n t_b \quad (69)$$

$$n t_b = (1/2n) \sum t_m (\cos n\pi x_{m-1}/\lambda - \cos n\pi x_m/\lambda) = (1/n) \sum t_m \sin [n\pi(x_m + x_{m-1})/2\lambda] \times \sin [n\pi(x_m - x_{m-1})/2\lambda]$$

= effective turns per pole, n th harmonic, phase b (70)

Each of these reactances must be corrected for skew

$$nX_a = nX'_a n C_{sk} = nX'_a [\sin(n\pi S_k/2\lambda)] / (n\pi S_k/2\lambda)$$

$$nX_b = nX'_b n C_{sk} \quad (71)$$

The amount of reactance that is deducted by this means is added to both the primary and secondary leakage reactance, as in equation 57.

It is convenient to take as the origin a point $\lambda/4$ from the center of the pole, as in Figure 1.

Appendix III. Sample Calculations for a Representative Motor

Partial List of Design Data—Dimensions in Inches

$$\begin{aligned} D &= 1.75 \\ D_r &= 1.65 \\ W &= 1.25 \\ P &= 4 \\ \lambda &= \pi 1.75/4 = 1.375 \\ S_c &= 0.00815 \\ S_r &= 0.02445 \\ S_s &= 25 \\ t_1 &= 250 \\ x_0 &= -\lambda/8 \\ x_1 &= 5\lambda/8 \end{aligned}$$

$$\Delta_{\min} = 0.015$$

$$\Delta_{\max} = 0.045$$

$$A_g = 0.815$$

$$T_f = 0.179$$

$$K_s = 1.36$$

$$R_1 = 22 \text{ ohms}$$

$$X'_1 = 10.0 \text{ ohms}$$

$$Sk = 4\lambda/25 = 0.22$$

Δ varies as in equation 1; stator iron is continuous.

Primary Reactances

$${}_0A = (1/2)(1/0.015 + 1/0.045) = 44.5$$

$${}_2A = (1/2)(1/0.015 - 1/0.045) = 22.45 \quad (1)$$

$${}_0\phi = 44.5 \times 0.815 \times 3.19 = 115.6$$

$${}_2\phi = 22.25 \times 0.815 \times 3.19 = 57.8$$

$$\begin{aligned} X_t &= 377 \times 10^{-8} \times 4 \times 1.25 \times 250^2 \times \\ &\quad [115.6(5\lambda/8 - \lambda/8) \times 1.375 + \\ &\quad 22.5(1.75/4) \cos(\pi/\lambda)(5\lambda/8 + \lambda/8) \times \\ &\quad \sin(\pi/\lambda)(5\lambda/8 - \lambda/8)] = 140.7 \text{ ohms} \end{aligned} \quad (61)$$

$${}_1a = 250 \left[\begin{aligned} &115.6 \cos(\pi/2\lambda)(5\lambda/8 - \lambda/8) \times \\ &\quad \sin(\pi/2\lambda)(5\lambda/8 + \lambda/8) \times \\ &\quad (57.8/2 \times 3) \cos(3\pi/2\lambda)(5\lambda/8 - \\ &\quad \lambda/8) \sin(3\pi/2\lambda)(5\lambda/8 + \lambda/8) - \\ &\quad (57.8/2) \cos(\pi/2\lambda)(5\lambda/8 - \lambda/8) \times \\ &\quad \sin(-\pi/2\lambda)(5\lambda/8 + \lambda/8) \end{aligned} \right] = 24,150 \quad (64)$$

$${}_1t_a = 250 \cos(\pi/2\lambda)(5\lambda/8 - \lambda/8) \times \sin(\pi/2\lambda)(5\lambda/8 + \lambda/8) = 163.2 \quad (57)$$

$${}_1X'_a = 377 \times 10^{-8} (8/\pi^2) 4 \times 1.25 \times 1.375 \times 163.2 \times 24,150 = 83.0 \text{ ohms} \quad (67)$$

$$1 - C_{sk} = (1/6)(\pi/2\lambda)^2 (4\lambda/25)^2 = 0.0105 \quad (21)$$

$${}_1X_{ska} = 0.0105 \times 83.0 = 0.872 \text{ ohm} \quad (19)$$

$${}_1X_a = 83.0 - 0.872 = 82.1 \text{ ohms}$$

Secondary Impedance

$$\begin{aligned} R_B &= \sqrt{1.25^2 + 0.22^2} \times 0.692 \times 10^{-6} / 0.00815 \\ &= 1.076 \times 10^{-4} \end{aligned} \quad (51)$$

$$R_r = 0.692 \times 10^{-6} / 0.02445 = 0.2825 \times 10^{-4} \quad (52)$$

$$\begin{aligned} K &= 4 \times 0.2825 \times 10^{-4} \times 1.65 \times 25/16 \\ &= 0.926 \times 10^{-4} \end{aligned} \quad (47)$$

$$\begin{aligned} X_s &= 377 \times 3.19 \times 10^{-8} \times 1.25 \times 1.36 \\ &= 0.293 \times 10^{-4} \end{aligned} \quad (53)$$

$$\begin{aligned} {}_0D &= 1.076 \times 10^{-4} + j(0.293 + 377 \times 10^{-8} \times \\ &\quad 3.19 \times 1.25 \times 0.179 \times 44.5/4) 10^{-4} \\ &= (1.076 + j 0.502) \times 10^{-4} \end{aligned} \quad (55)$$

$${}_2D = j 377 \times 10^{-8} \times 3.19 \times 1.25 \times 0.179 \times 22.25/4 = j 0.1495 \times 10^{-4} \quad (56)$$

$${}_1G_a = 4 \times 16 \times 163.2^2/25 = 6.83 \times 10^4 \quad (48)$$

$$\begin{aligned} {}_1Z_a &= 6.83 [(2 \times 1.076 + 0.926) + j(2 \times 0.502 - \\ &\quad 0.1495)] - j 0.872 \\ &= 21.05 + j 6.71 \end{aligned} \quad (49)$$

Computation of the other constants is similar.

Summary of Constants

$$\begin{aligned} {}_1X_a &= 82.1 \text{ ohms} & {}_2X_a &= 3.327 \text{ ohms} \\ {}_1X_{2a} &= 6.71 & {}_2X_{2a} &= 1.519 \\ {}_1X_{oa} &= 88.81 & {}_2X_{oa} &= 4.846 \\ {}_1X_b &= 45.72 & {}_2X_b &= 1.073 \end{aligned}$$

$$\begin{aligned} {}_1X_{23} &= 8.37 \\ {}_1X_{2b} &= 54.1 \\ {}_1R_2 &= 21.05 \\ R_1 &= 22 \text{ ohms} \\ X_1' &= 10 \\ X_1 &= 140.7 \\ {}_1X_a - {}_1X_b &= 36.38 \\ {}_1X_{2b} - {}_1X_{2a} &= 1.665 \\ {}_2X_a - {}_2X_b &= 2.254 \\ {}_2X_{2b} - {}_2X_{2a} &= -0.233 \end{aligned}$$

Starting Conditions

$$\begin{aligned} {}_1K_{ra} &= (82.1/88.8)^2 / (1 + (21.05/88.8)^2) \\ &= 0.810 \\ {}_1K_a &= (0.810/82.1)(88.8 + j21.05) \\ &= 0.875 - j0.208 \end{aligned} \quad (12)$$

Likewise

$$\begin{aligned} {}_1K_b &= 0.735 + j0.2855, {}_2K_a = 0.529 + j0.288, \\ {}_2K_b &= 0.2025 + j0.2265 \end{aligned}$$

The total impedance is

$$\begin{aligned} &22 + j150.7 \\ -j82.1(0.875 + j0.208) &= 17.1 - j71.9 \\ -j45.72(0.735 + j0.2855) &= 13.08 - j33.6 \\ -j3.33(0.529 + j0.288) &= 0.96 - j1.76 \\ -j1.07(0.2025 + j0.2265) &= 0.23 - j0.22 \\ &53.27 + j43.1 \\ &= 68.5/39^\circ 00' \end{aligned}$$

$$I = 110/68.7/39^\circ 00' = 1.60/-39^\circ 00' \text{ amperes}$$

$$\text{Power factor} = \cos 39^\circ 00' = 0.778$$

$$W = 110 \times 1.60 \times 0.778 = 137 \text{ watts, input}$$

$$\begin{aligned} {}_1T &= (11.3 \times 4 \times 0.810 \times 0.618/60 \times 82.1 \times \\ &45.72)1.6^2 [1.665(21.05^2 - 88.8 \times \\ &54.1) - 2 \times 36.38 \times 21.05^2] \\ &= 0.000256(1.665 \times (-4,368) - 2 \times \\ &36.38 \times 442) \\ {}_1T &= 0.000256(-7,270 - 32,200) \\ &= -10.12 \text{ ounce-inches} \end{aligned} \quad (13)$$

The greatest contribution to ${}_1T$ in this case is seen to be from ${}_1R_2^2({}_1X_a - {}_1X_b)$. In the same manner

$${}_2T = -1.632 \quad T = {}_1T + {}_2T = -11.7 \text{ ounce-inches}$$

Although the third harmonic does not affect the current greatly, it is seen to contribute

appreciably to the torque. Using the more complete formula of equation 45, $T = -10.6$ ounce inches.

Running Conditions

Let

$$\begin{aligned} S &= -0.85 \quad 1 - S^2 = 0.2775 \\ -0.85 \times 21.05 \times 45.72 &= -818 \\ -0.2775 \times 54.1 \times 82.1 &= -1,234 \\ {}_1F_a &= -2,025 + j1,730 \\ j21.05 \times 82.1 &= j1,730 \quad (6) \\ -(-0.85) \times 21.05 \times 82.1 &= 1,470 \\ -0.2775 \times 88.8 \times 45.7 &= -1,125 \\ {}_1F_b &= 345 + j963 \\ j21.05 \times 45.7 &= j963 \quad (7) \\ 21.05^2 &= 443 \\ -0.2775 \times 88.8 \times 54.1 &= -1,333 \\ {}_1F &= -891 + j3,010 \\ j21.05(88.8 - 54.1) &= j3,010 \quad (8) \end{aligned}$$

$$\begin{aligned} {}_1K_a &= (-2,052 + j1,730)/(-891 + j3,010) \\ &= 0.714 - j0.470 \quad (5) \end{aligned}$$

$$\begin{aligned} {}_1K_b &= (345 - j963)/(-891 + j3,010) \\ &= 0.262 - j0.193 \quad (6) \end{aligned}$$

If ${}_2K_a$ and ${}_2K_b$ are computed and equation 9 is used again

$$\begin{aligned} Z_0 &= 93.1/56^\circ 20' \\ I &= 1.18/-56^\circ 20' \text{ amperes} = 0.653 - \\ &j0.981 \text{ ampere} \end{aligned}$$

$$\text{Power factor} = 0.55$$

$$\text{Input} = 71.4 \text{ watt (iron losses to be added)}$$

$$\begin{aligned} {}_1U &= 0.714 \quad {}_1u = 0.470 \\ {}_1V &= 0.262 \quad {}_1v = -0.193 \\ {}_1U_1V - {}_1u_1v &= 0.714 \times 0.262 - 0.470 \times \\ &0.193 = 0.0961 \\ {}_1T &= (11.3 \times 4/60)1.18^2 [(0.262 - 0.0961) \times \\ &82.1 - (0.714 - 0.0961)45.7] = -15.3 \end{aligned}$$

Likewise

$$\begin{aligned} {}_2T &= 2.95 \\ T &= {}_1T + {}_2T = -12.3 \text{ ounce inches} \\ \text{Output} &= 0.001782 \times 0.85 \times 12.3 = 0.0186 \\ &\text{horsepower} \\ \text{Output} &= 0.0186 \times 746 = 13.9 \text{ watts} \\ \text{Efficiency (disregarding iron losses)} &= 13.9 \times \\ &71.4 = 19.5 \text{ per cent} \end{aligned}$$

Iron Losses

Let

$$\begin{aligned} \text{Hysteresis coefficient, } \eta &= 0.003 \\ \text{Conductivity of iron} &= 10^5 \\ \text{Thickness of laminations} &= 0.03 \\ \text{Cross section of half of flux path} &= 0.390 \\ \text{Volume of iron} &= 10.3 \\ \text{Maximum flux density} &= B_m \\ \text{Hysteresis loss per cubic inch} &= {}_h w \\ \text{Eddy-current loss per cubic inch} &= {}_e w \\ {}_h w &= 8.3 \times 10^{-8} \times 0.003 \times 60 B_m^{1.6} = 1.495 \times \\ &10^{-8} B_m^{1.6} \text{ watts per cubic inch} \\ {}_e w &= 4.18 \times 10^{-18} \times 10^5 \times 0.03^2 \times 60^2 B_m^2 \\ &= 1.353 \times 10^{-10} B_m^2 \text{ watts per cubic inch} \end{aligned}$$

To obtain the voltage drop due to the flux, deduct the primary IR (current resistance) drop from the applied voltage

$$\begin{aligned} E_\phi &= 110 - 22 \times 1.18 / -56^\circ 20' \\ &= 98.1/12^\circ 44' \\ \phi_p &= E_\phi / 2\pi f 10^{-8} \text{ } P = \text{flux per pole} \\ \phi_p &= 98.1/377 \times 10^{-8} \times 250 \times 4 = 2.60 \times 10^4 \\ B_m &= 2.60 \times 10^4 \times \sqrt{2}/2 \times 0.390 = 4.71 \times 10^4 \\ &\text{lines per square inch} \\ {}_h w &= 1.495 \times 10^{-8} (4.71 \times 10^4)^{1.6} = 0.449 \\ {}_e w &= 1.353 \times 10^{-10} (4.71 \times 10^4)^2 = 0.301 \end{aligned}$$

$$\begin{aligned} &0.750 \text{ watt} \\ &\text{per cubic inch} \end{aligned}$$

$$\begin{aligned} W &= 10.3 \times 0.750 = 7.73 \text{ watts, total iron loss} \\ 7.73/98.1/12^\circ 44' &= 0.0788/-12^\circ 44' \\ &= 0.0770 - j0.0146 = \text{iron-loss current} \\ 0.653 - j0.981 + 0.0770 - j0.0146 &= 0.730 - \\ &j0.996 = 1.24/-53^\circ 45' = \text{total current} \end{aligned}$$

$$\begin{aligned} 71.4 + 7.8 &= 79.2 \text{ watts, total input} \\ 13.9/79.2 &= 17.9 \text{ per cent efficiency} \end{aligned}$$

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An Eight-Year Investigation of Lightning Currents and Preventive Lightning Protection on a Transmission System

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SOME 10 or 12 years ago effective lightning protection began to be applied to transmission lines, and, about the same time, an inexpensive measuring device (the surge-crest ammeter) was developed.¹ On one transmission system this low-cost device has been applied to every structure in entire lines and has produced definite numerical evidence of the performance of the protection provided.

It is shown that on the system studied, the distribution of lightning strokes occurs at random, and that there are great variations in the number and intensity of strokes from year to year. The numerical data show that the gain would be small from protection of single structures or sections of lines. The data also make it possible to estimate long-time line performance from short-time records. The surge impedance of an overhead ground wire is indicated to be less than 235 ohms instead of the generally accepted value of 400 to 500 ohms.

The counterpoise arrangements on the lines in question vary from a single wire to eight wires in multiple. There is no evidence to show that one arrangement is better than another, as long as the resulting ground-resistance value is the same. The bonding of structures at crossings and parallels shows no tendency to spread trouble from one structure to another. Arresters connected to well-protected lines were seldom caused to operate, and, when they did, the currents in most cases were small.

Scope of Field Investigation

The installation of surge-crest-ammeter links was begun on a system in Pennsylvania and Maryland in June 1934, with additional installations being made every succeeding year. By the end of

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1942, brackets were installed on transmission-line steel structures, lightning arresters, overhead ground wires, lightning rods, and a steel flagpole. The aggregate exposure of the links has been considerable on the lines, amounting to 13,227 tower-years and 1,776 mile-years with 5,501 bracket records obtained. The exposure on the lightning arresters connected at the terminals of the lines

Table I. Variation in Total Number of Strokes Recorded Yearly on Five Transmission Lines

Year	Strokes Recorded	Ratio to Five-Year Average
1938.....	239.....	1.05
1939.....	283.....	1.25
1940.....	252.....	1.11
1941.....	163.....	0.72
1942.....	199.....	0.88
Average.....	227	

has been 155 bank-years, with 54 records obtained. No significant records were obtained from the few miscellaneous bracket installations.

Frequency of Strokes to Lines

Two 220-kv lines, one 132-kv line, and two 66-kv lines cover the area served by the system. The stroke records from

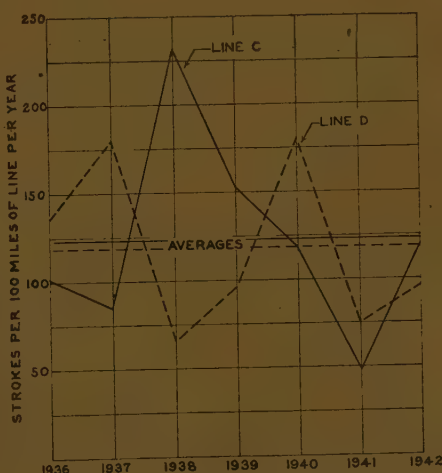


Figure 1. Strokes to two 66-kv lines

these five lines, having an aggregate length of 228 miles, are taken as giving a representative picture of lightning conditions on the system. Table I shows how the number of strokes recorded on these lines varied from year to year. The ratio of the yearly maximum of recorded strokes to the minimum is 1.74.

When the records of individual lines are examined, the variations become more pronounced. This is demonstrated in Table II, which is the record for the four transmission lines on which tower lightning currents have been measured for the longest time. As is to be expected, the range of yearly variations is greater for single lines than for the system as a whole. Also, the longest line does not show so wide a range in the number of recorded strokes as do the shorter lines. Beyond these generalizations, the data show random behavior. For instance, in Figure 1 are given records of two comparable lines, both lying in a more or less east-west direction and having very nearly the same stroke density. In 1938 line C received its peak number of strokes for its seven years of record, while line D received the lowest number of strokes for the same time.

These wide variations are indicative of the difficulty of judging the value of any lightning-protective scheme from short-time field-performance data. Table III shows how the average recorded stroke frequency for a small number of consecutive years can be quite far from representative of the long-time experience. In this table, seven- and eight-year records are assumed to be representative samples of the long-time record. This assumption seems reasonable for all practical purposes.

As was to be expected, the average stroke frequency for any number of consecutive years usually did not deviate from the period average as widely on line A, 91.8 miles long, as it did on the shorter lines. A long line has a good chance of being in the path of most local thunderstorms, some of which might miss shorter lines.

In Table III, the large ratios of maximum to minimum number of strokes recorded yearly help explain the common experience of a line behaving well one year and poorly the next.

Frequency of Strokes to Individual Towers

Repeated lightning trouble at a given tower during a relatively short period of one or two years often is considered indicative of a location particularly sub-

Table II. Recorded Strokes to Lines Per 100 Miles Per Year

	Line A 220 Kv	Line B 132 Kv	Line C 66 Kv	Line D 66 Kv	Average Values
Length of line in miles.....	91.8	33.8	29.4	22.8	
Period of record in years.....	8	8	7	7	
Average strokes for period.....	95	135	123	119	118
Maximum in one year.....	129	219	232	180	190
Ratio to period average.....	1.36	1.62	1.89	1.51	1.61
Minimum in one year.....	59	86	48	66	65
Ratio to period average.....	0.62	0.64	0.39	0.56	0.55
Ratio of yearly maximum to yearly minimum.....	2.19	2.54	4.85	2.73	2.92

1,364 mile-years of line are represented by above record.

System average strokes per 100 miles of line per year is 113 for five observed lines totaling 1,617 mile-years of experience.

Table III. Ratio of Average Stroke Frequency for Consecutive Years to the Average for an Entire Period of Record

Indicated Number of Consecutive Years	Period of Record (Years)			
	8 Line A	8 Line B	7 Line C	7 Line D
One year records { Maximum.....	1.36	1.62	1.89	1.52
{ Minimum.....	0.62	0.64	0.39	0.56
Averages for two consecutive years { Maximum.....	1.29	1.36	1.57	1.34
{ Minimum.....	0.77	0.70	0.68	0.68
Averages for three consecutive years { Maximum.....	1.18	1.31	1.37	1.07
{ Minimum.....	0.82	0.76	0.79	0.96
Averages for four consecutive years { Maximum.....	1.06	1.28	1.20	1.10
{ Minimum.....	0.85	0.86	0.90	0.88
Averages for five consecutive years { Maximum.....	1.10	1.19	1.13	1.11
{ Minimum.....	0.89	0.93	1.04	0.87
Averages for six consecutive years { Maximum.....	1.08	1.10	1.03	1.03
{ Minimum.....	0.91	0.96	1.00	1.03
Averages for seven consecutive years { Maximum.....	1.02	1.05		
{ Minimum.....	0.95	1.04		

ject to lightning. Inasmuch as the records on lines *A* and *B* have been kept for eight complete years, some data are available which show what can be expected. Table II shows that a unit length of line *A* is struck, on the average, about 70 per cent as often as a unit length of line *B*. The effect of the greater number of strokes to line *B* is shown in the greater percentages of towers struck and struck more frequently (Table IV). The percentages of towers of both lines that were struck one, two, and three times are nearly equal.

There were 104 cases on lines *A* and *B* during the eight years of record in which an individual tower was struck two years in succession, 15 cases in which a tower was struck three consecutive years, and

only three cases in which individual towers were struck four years in succession.

Towers rarely were struck more than once in a single year. On lines *A* and *B* there were 63 cases in which towers were struck twice in a single year, and only one case in which three strokes to an individual tower were recorded.

Table V shows that towers can pass through several years without being struck. If this should occur where no lightning-recording device is used, it might be inferred that the lightning protection is quite good, when in reality there has been an absence of strokes. A period of freedom from lightning strokes may be followed by a period of frequent strokes. The detailed records from the

towers of these two lines show all types of distribution of strokes during the eight-year period. From these data it appears that no tower is more subject to lightning than another except by chance.

Variations in Lightning Intensity

In addition to the variation in the number of strokes striking a line, a variation in their intensity also affects performance. Figure 2 shows the distribution of tower currents during a long period of time.

In any one year the percentage of tower currents exceeding any given value may be quite different from the average for a long period. This is shown in Table VI. Since both the stroke frequency and intensity seem to be random phenomena, a number of years sometimes elapses between flashovers on a fairly well-protected line that is faulted by only high-intensity strokes. The other extreme condition, in which there are a number of flashovers in one year, or even during one storm, sometimes occurs. A rare instance of this latter type of trouble occurred during 1942 on the 66-kv line *C*, when five towers covering a distance of 1.9 miles experienced flashovers, although only one simultaneous double-circuit tripout occurred.

An interesting and perhaps significant phenomenon appears in Figure 2. For some years on this distribution curve of tower currents, the points for 30,000 amperes and less have followed a wavy line such as shown by the broken line in Figure 2. Up to this time,² the apparent irregularity in the points was thought to be the result of insufficient data, but now, with 1,987 cases accumulated, this original explanation appears to be incorrect. All of the data obtained thus far (1934-42) have been plotted in 5,000-ampere groups in Figure 3. It will be seen that the maximum number of cases has occurred in the 5,000- to 10,000-

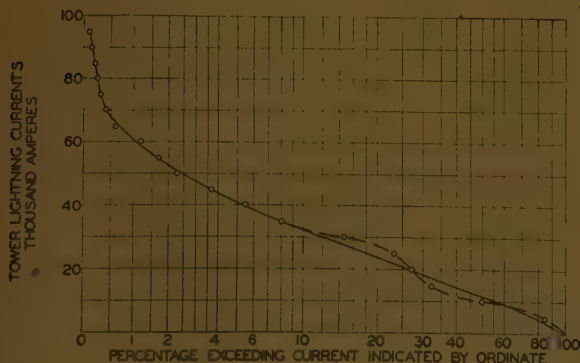


Figure 2. Distribution of 1,987 currents measured in towers believed struck by lightning

Table IV. Number of Times Individual Towers Have Been Struck by Lightning During an Eight-Year Period

Number of Times Struck	Towers Struck the Indicated Number of Times			
	Line A		Line B	
	Number	Per Cent	Number	Per Cent
0.....	115	24.1	23	12.9
1.....	163	34.2	63	35.2
2.....	106	22.2	41	22.9
3.....	71	14.9	26	14.5
4.....	15	3.2	19	10.5
5.....	5	1.0	4	2.3
6.....	2	0.4	2	1.1
7.....	0	0	1	0.6
	477		179	

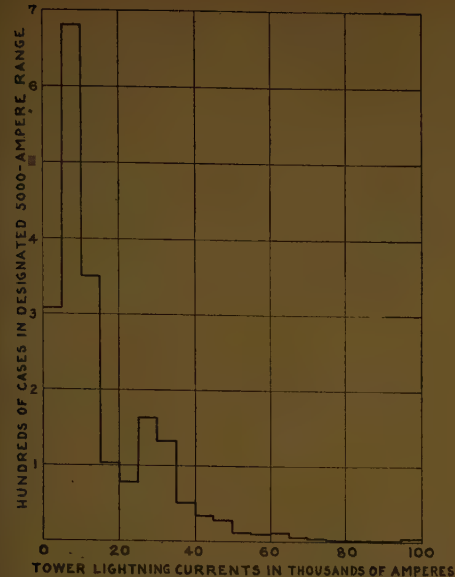


Figure 3. Range distribution of 1,987 currents in towers believed struck by lightning 1934-42

ampere range, with a secondary peak occurring in the 25,000- to 30,000-ampere range. To investigate whether or not this phenomenon is the result of some unusual records obtained during the early part of the period of study which influenced the entire set of data, the data from individual years in which records were complete were plotted by percentage in Figure 4. The primary peak is quite pronounced every year in

Table V. Towers Not Struck in Successive Years During an Eight-Year Period

Years in Succession in Which a Tower Was Not Struck	Number of Cases	
	Line A	Line B
1.....	200.....	122
2.....	167.....	65
3.....	133.....	62
4.....	98.....	40
5.....	67.....	27
6.....	57.....	19
7.....	38.....	13
8.....	115.....	23

Table VI. Range of Per Cent of Tower Currents in Single Years Exceeding Indicated Value

Tower Amperes	Range of Yearly Per Cent*		Average Per Cent 1934-42
	Minimum	Maximum	
10,000.....	37.5.....	65.4.....	50
20,000.....	13.4.....	39.....	27.1
30,000.....	6.2.....	20.....	14.8
40,000.....	0.8.....	9.2.....	5.5
50,000.....	0.....	4.1.....	2.3
60,000.....	0.....	2.0.....	1.2
70,000.....	0.....	1.2.....	0.4
80,000.....	0.....	0.8.....	0.25
90,000.....	0.....	0.6.....	0.15
100,000.....	0.....	0.....	0

* Eight-year record, 1935-42. Records were not obtained for the entire 1934 lightning season, but the records obtained in that year are included in the average values given in the last column.

Table VII. Ratio of Sum of Four Leg Currents, Representing Probable Tower Current, to Four Times the Single-Leg Current

Tower Current (Four Times Single- Leg Current)	Number of Leg Records	Ratio of Sum of Four Leg Currents to Four Times Single-Leg Current		
		Average	Median	Range
1- 1,000.....	28.....	5.39.....	2.42.....	1.42-49.5
1,001- 2,000.....	21.....	3.78.....	2.69.....	0.93-17.8
2,001- 5,000.....	46.....	1.24.....	1.07.....	0.25- 3.75
5,001- 7,500.....	48.....	0.89.....	0.82.....	0.25- 2.88
7,501-10,000.....	59.....	1.13.....	1.02.....	0.25- 4.13
10,001-15,000.....	87.....	1.01.....	0.97.....	0.30- 1.85
15,001-20,000.....	17.....	1.17.....	0.91.....	0.33- 4.25
20,001-25,000.....	13.....	0.89.....	0.88.....	0.28- 1.25
25,001-30,000.....	23.....	0.82.....	0.84.....	0.47- 1.10
30,001-35,000.....	17.....	0.80.....	0.82.....	0.26- 1.27
35,001-40,000.....	9.....	1.03.....	1.01.....	0.73- 1.23
40,001-45,000.....	1.....	1.13.....	1.13.....	
45,001-50,000.....	4.....	0.89.....	0.89.....	0.82- 0.95
50,001-55,000.....	4.....	0.85.....	1.00.....	0.25- 1.14
55,001-60,000.....	5.....	0.94.....	1.01.....	0.77- 1.03
60,001-65,000.....	3.....	0.97.....	0.97.....	0.93- 1.02
65,001-70,000.....	2.....	0.93.....	0.93.....	0.88- 0.98
76,000.....	1.....	0.52.....	0.52.....	
80,001-85,000.....	2.....	0.37.....	0.37.....	0.25- 0.48
114,000.....	1.....	0.57.....	0.57.....	
		391		

the 5,000- to 10,000-ampere range. The secondary maximum in the 25,000- to 30,000-ampere range is quite apparent in the records from 1935, 1938, 1940, 1941, and 1942. It is less prominent in the 1937 and 1939 records. The secondary maximum occurs in the 20,000- to 25,000-ampere range in 1936.

This analysis makes it appear that the wavy form of the broken line curve in Figure 2 is a more accurate representation of the distribution of tower currents below 35,000 amperes than is the straighter line. It appears that there are two principal types of lightning discharges as far as tower currents are concerned. Most of one type produce tower currents in the 5,000- to 10,000-ampere range, and most of the other type produce them in the 25,000- to 30,000-ampere range.

Division of Lightning Currents in Legs of Towers

Most of the tower lightning currents have been measured in towers where surge-crest-ammeter brackets have been mounted on only one leg. The tower current in such cases has been assumed to be four times the current measured in the leg having the bracket. Of principal interest are the records from towers which it is believed have been struck by lightning or are adjacent to struck spans of overhead ground wire, because it is these towers which are subject to flash-overs.

It is believed that there have been 104 times when towers provided with surge-crest-ammeter brackets on all four legs have been hit. These 416 records permit an estimate to be made of the errors in-

involved when the tower current is computed from the current in a single leg.

Each of the 104 sets of records has been analyzed by first adding the four leg currents to obtain the nominal tower current. Then, each record was treated as if it were the only one available from a tower. In Table VII are data on the ratio of the sum of the four leg currents in a tower to the product of four times the single leg currents taken individually. If one assumes that the sum of the four leg currents is a good representation of the true tower current, the probable tower current can be obtained from a single-leg record by the relation:

$$\text{Probable tower current} = 4 \times \text{leg current} \times \text{ratio from Table VII}$$

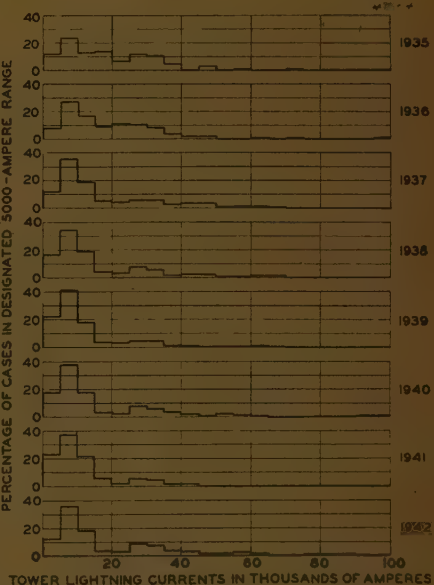


Figure 4. Range distribution of tower lightning currents by years

Table VIII. Lightning Disturbances on Parallel 66-Kv Lines

40 Miles—415 Towers

Observation Period (Years of Record)												
1918-31 14 (No Grounding)			1932-34 3 (Single Bonds Towers 6-90)			1935-38 4 (Single Bonds Towers 6-332)			1939-42 4 (Double Bonds and Counterpoise—Towers 6-415— Entire Line)			
Number During Period	Average Number Per Year	Per Cent	Number During Period	Average Number Per Year	Per Cent	Number During Period	Average Number Per Year	Per Cent	Number During Period	Average Number Per Year	Per Cent	
Disturbances involving one circuit.....	91.....	6.5.....	46.5.....	11.....	3.7.....	31.4.....	9.....	2.3.....	47.4.....	2.....	0.5.....	50
Disturbances involving two circuits on only one line.....	95.....	6.8.....	48.5.....	15.....	5.0.....	42.9.....	8.....	2.....	42.1.....	0.....	0.....	0
Disturbances involving circuits on both lines.....	10.....	0.7.....	5.0.....	9.....	3.0.....	25.7.....	2.....	0.5.....	10.5.....	2.....	0.5.....	50
Totals.....	196.....	14.....	100.....	35.....	11.7.....	100.....	19.....	4.8.....	100.....	4.....	1.....	100

For instance, there was a case of flash-over in which the tower lightning current was calculated from one leg-current record as being 13,400 amperes. This current lies in the range 10,001 to 15,000 amperes in Table VII. The median ratio is 0.97 in this range, which indicates that there is an even chance that the tower current was more or less than $0.97 \times 13,400$ amperes = 13,000 amperes. However, experience with 87 records in this range indicates that the current possibly may have been anywhere in the range 0.30 to $1.85 \times 13,400$ amperes, or between 4,000 and 24,300 amperes.

The values of the median ratio being near unity in most cases in Table VII indicates that, on the average, results throughout most of the range of the currents measured are of fairly uniform accuracy. The low values of the median ratio for tower currents above 70,000 amperes and the high values below 2,000 amperes suggest that currents indicated in these ranges by single-leg records are often appreciably different from four times the single-leg value.

There were 25 cases in which there was no indication of current in a tower leg but in which the sum of the four leg currents in the given tower indicated that the tower had been struck by lightning. In these cases, if brackets had been mounted only on the legs yielding no records, no record of the strokes would have been obtained. Actually the tower currents ranged from 800 to 6,200 amperes, averaging about 2,200 amperes. These data and those in Table VII suggest that there may be $25/(416-25) \times 100 = 6.4$ per cent more strokes to a line than indicated by the surge-crest-ammeter links if there is only one bracket on each tower. It thus appears that the absence of a record on a tower having a single bracket does not mean necessarily that the tower has not been struck by light-

ning. The data also imply that it probably would be quite difficult to arrive at a satisfactory constant factor to account for currents carried by tower cross members, because the current distribution in cross members probably varies as widely as that in the legs.

Effect on Flashovers of Bonding Adjacent Towers

There have been three instances of flashover on neighboring towers where footings are bonded with buried conductors. Two of these were simultaneous flashovers on two lines carrying two circuits each and situated on the same right of way with 50 feet separation. Table VIII summarizes the lightning experience on these lines in the 25-year period 1918-42. During this period the lines operated 14 years without bonding. When adjacent towers on about three quarters of the line were bonded, the four-year period 1935-38 showed only 4.8 disturbances per year as compared to an average of 14 in the period without bonding.

Before the bonding was installed there were 0.7 disturbance per year involving circuits on both lines, and after the bonding was installed there were 0.5 disturbance per year of this type.

The third instance of flashover occurred on a tower of line C, which is shielded by the much taller tower of line B. The footings of the two towers are bonded together. When flashover occurred on the line-C tower, there was no flashover of the line-B tower, although the latter tower current was about 80,000 amperes. This current gives a tower-footing resistance drop of around 930-kv. Apparently the 132-kv tower was struck, but the potential of the 66-kv tower was raised through the bonding to a level sufficient to flash over. During the period of record previous to the flashover

in 1942, there were ten strokes to the towers at this intersection without any flashover. The tower currents were all 38,000 amperes or less.

These three instances of trouble at bonded towers raise a question about the value of bonding neighboring transmission towers, but the complete record of tower lightning currents makes it appear that bonding is helpful in reducing the total number of flashovers on adjacent towers if the bonding can reduce footing resistances. There seems to be no effect of bonding on multiple-line disturbances. Table VIII shows the total number of disturbances reduced further by the installation of counterpoise. The number of simultaneous flashovers appears to remain constant, but becomes a greater percentage of the total number of disturbances with improvement of grounding.

Efficacy of Continuous Counterpoise

Examination of Table IX shows that as many as eight continuous counterpoise

Table IX. Flashovers Believed Caused by Strokes to Towers or Overhead Ground Wires on 66-Kv Lines Provided With Preventive Protection

Type of Counterpoise	Number of Cases	Tower Footing (Ohms)	Ratio of Footing Resistance Drop to Tower Flash-over Level
8 continuous	2.....	3.6, 5	..0.26, 0.37
6 continuous	2.....	10.5, 17	..0.75, 0.91
5 continuous	2.....	4.6, 9	..0.26, 0.38
4 continuous	2.....	13.8, 19	..0.82, 1.16
3 400 feet+...	2.....	11.8, 17.2	..1.25, 1.80
2 continuous	1.....	5.4	..0.38
11			

There has been one flashover on a 132-kv tower (137 feet high):
Footing (ohms) 12.2
Footing resistance drop = 0.41
Tower flashover level
Counterpoise: Four continuous+4 300 feet

connected to a 66-kv tower do not produce a surge impedance low enough to prevent flashovers. These lines have insulator flashover values of 565-635 kv with a $1\frac{1}{2} \times 40$ -microsecond wave. In a number of cases the ground resistance was quite low, making the tower potentials based on the product of tower current times tower-footing resistance only a small fraction of the value expected to produce flashover. Since flashover occurred with such low footing resistance it seems reasonable that the inductive reactance drop was largely responsible and that the footing resistance might be higher without additional flashovers occurring. Measurements show that the omission of the four inner conductors of the counterpoise system, where the ground resistance is 3.6 ohms, would raise the ground resistance of the remaining counterpoise, consisting of four conductors, to about 4.5 ohms. The inner conductors were originally installed in the hope that the surge impedance would be reduced sufficiently to prevent flashovers. The experience listed in Table IX shows that this hope was not realized. It thus appears that no benefit is derived from adding counterpoise wires after the ground resistance has been reduced to the optimum value.³

Line B has an insulator flashover level of 1,015 kv. The only flashover on this line was at a tower 137 feet high, which is about twice the height of the 66-kv towers. It seems likely that the surge impedance added by the greater tower height contributed to the conditions causing flashover. The product of tower-footing resistance times tower current is only 41 per cent of the theoretical tower potential required for flashover. The eight-year record of line B indicates that multiple counterpoise systems having the optimum ground resistance of ten ohms or less prevented flashovers.

The 220-kv lines have an insulator flashover level of 1,605 kv, for which the optimum footing resistance is 16 ohms.³ Since very low footing resistances were not required, an experimental installation of single counterpoise, continuous in both directions to the next adjacent towers, was made at 38 towers of a 220-kv line. The lightning-current records have been kept on these towers for nine years, making a total of $9 \times 38 = 342$ tower years of record without flashover. Sixty-four strokes were recorded on the towers during this period, producing tower currents as great as 98,000 amperes. The footing resistances did not exceed 20 ohms. The data seem to indicate that towers having an insulator flashover level of about 1,600 kv are quite well protected

by single continuous counterpoise, provided this type of grounding will bring the footing resistances down to the optimum value.

Estimated Maximum Apparent Surge Impedance of an Overhead Ground Wire

Table X gives 17 instances when tower currents of about 30,000 amperes or greater have been recorded in two adjacent towers of a line and the currents have not differed from each other by more than 25 per cent of the larger tower current.

Table X. Estimate of Maximum Value of Surge Impedance of an Overhead Ground Wire

Mid-Span Spacing Between Overhead Ground Wire and Nearest Line Conductor	Span Length in Feet	Nominal Voltage (Kv) to Produce Flashover at Mid-Span (1 Microsecond Front)	Lightning Currents in Adjacent Towers	Maximum Surge Impedance (Ohms) Without Flashover
15.8.....	810.....	5,020.....	{ 36,200 } { 35,200 }	139
23.8.....	780.....	7,560.....	{ 33,200 } { 30,000 }	228
27.2.....	1,020.....	8,650.....	{ 30,000 } { 30,000 }	289
28.5.....	790.....	9,060.....	{ 41,600 } { 41,200 }	223
28.5.....	915.....	9,060.....	{ 34,800 } { 31,200 }	261
29.5.....	1,250.....	9,380.....	{ 40,400 } { 39,200 }	232
29.9.....	1,100.....	9,500.....	{ 43,200 } { 38,000 }	220
30.1.....	980.....	9,560.....	{ 47,200 } { 39,200 }	203
30.1.....	1,000.....	9,560.....	{ 34,800 } { 31,200 }	275
30.1.....	1,000.....	9,560.....	{ 48,800 } { 40,000 }	196
30.1.....	1,000.....	9,560.....	{ 47,600 } { 38,200 }	200
31.6.....	1,150.....	10,050.....	{ 42,800 } { 33,600 }	235
32.1.....	1,210.....	10,200.....	{ 35,000 } { 30,400 }	292
32.8.....	1,250.....	10,400.....	{ 37,600 } { 30,600 }	276
33.3.....	1,290.....	10,600.....	{ 32,800 } { 29,200 }	323
33.8.....	1,320.....	10,750.....	{ 53,200 } { 42,400 }	202
34.2.....	1,750.....	10,900.....	{ 50,400 } { 44,400 }	216

A pair of records of this type has been interpreted as resulting from a stroke to an overhead ground wire about midway between towers. The current in the overhead ground wire is probably as great as, or greater than the indicated tower current, because some current probably flows in the overhead ground wire, or wires, past the recording tower and does not affect the surge-crest-ammeter links.

Since no tripouts occurred in any of these cases, there is assurance that no flashovers occurred at any of these locations. Incidentally, flashovers causing tripouts have been at towers, not in mid-span. In Table X the voltage required to flash over the mid-span spacing and the probable minimum value of the lightning current in the overhead ground wire are

given. The probable upper limit for the surge impedance of the overhead ground wire is the foregoing voltage divided by the corresponding tower current. The average value of the surge impedance, calculated in this way, is 236 ohms, the median is 228 ohms, and the range is from 139 to 323 ohms. These values for the surge impedance of a conductor in air are appreciably less than the theoretical value of 400 or 500 ohms often quoted. Of more practical interest is the implication from these data that mid-span clearances may not need to be so great as often are allowed. Perhaps the preven-

tion of sleet and snow troubles, rather than the prevention of mid-span lightning flashovers, should be the controlling factor in determining mid-span clearances.

Comparison of Estimated and Actual Lightning Performance

Published literature on lightning protection indicates over 20 factors probably affecting the estimated lightning performance of a transmission line (see appendix). The individual effect of most of these factors is known only qualitatively, and so it is practically hopeless to include them in any estimating method. Relatively simple calculations were attempted in 1937 for estimating the line interruptions which might be expected as a result of lightning.^{3,4} From the records available,

Table XI. Estimated and Actual Lightning Outages

Line	Years of Record	Lightning Outages Per Year		Error (Per Cent)
		Actual	Estimated	
A—220 kv.....	11.....	0.09.....	0.014.....	**
F—220 kv.....	5.....	0.....	0*.....	**
B—132 kv.....	8.....	0.13.....	0.05.....	**
E—66 kv.....	4.....	1.....	1.....	0
C—66 kv.....	5.....	1.....	1.3.....	+30
Before improvement (1928-36).....	9.....	17.9.....	21.0.....	+17
D—66 kv.....	.....	.....	.....	.....
Before improvement (1929-34).....	6.....	19.3.....	20.6.....	+7

* Does not include a one-mile section where there are no overhead ground wires.

** It will take many more years of operation to check the accuracy of estimates for these lines because flashovers so seldom occur.

Table XII. Efficiency of Preventive Lightning Protection During Period of Study With Surge-Crest-Ammeter Links

Line	Years of Record	Lightning Outages*	Trippouts Per 100 Miles of Line Per Year		Efficiency of Protection (Per Cent)
			Recorded	Strokes	
A—220 kv.....	8.....	0.....	0.....	696.....	100
F—220 kv.....	5.....	0.....	0.....	223.....	100
B—132 kv.....	8.....	1.....	0.39.....	354.....	99.7
C—66 kv.....	.....	.....	.....	.....	.....
Before improvements.....	2.....	37.....	63.....	55.....	33
After improvements.....	5.....	5.....	3.4.....	198.....	97.5
Suspension towers.....	4**.....	.....	.....	143.....	97.2
Strain towers.....	4**.....	.....	.....	55.....	92.7
E—66 kv.....	4.....	4.....	1.3.....	236.....	98.3
(Two lines on one right of way)	.....	.....	.....	.....	.....

* Single, double, and triple circuit trippouts. ** Flashovers.

the method seems to work well for shielded lines. As a further check, and to determine if the method also applies to unprotected lines, additional calculations were made for lines C and D before they were improved. The results are shown in Table XI.

Line D, before it was improved, is of particular interest because of its non-uniformity. The line is 22.8 miles long, and approximately 2.1 miles on each end were provided with a single overhead ground wire. There was no auxiliary grounding anywhere on the line. Detailed calculations for estimating the performance are given in the appendix, and indicate that 20.6 trippouts per year could be expected. This is an error of only seven per cent from the actual experience, as shown in Table XI.

Efficiency of Preventive Protection

The efficiency of the protection provided by the combination of insulation, grounding, and shielding can be calculated from the stroke and trippout records. Efficiency of protection is the ratio, expressed in per cent, of the number of strokes not causing trippouts to the total number of strokes. Table XII gives the record for all lines. The record of line D is omitted from this table, because this line is provided with a Petersen coil as

well as preventive protection. It has suffered no lightning troubles during five years' operation with this double protection.

The better efficiency of protection for the suspension towers of line C as compared to the strain towers is probably the result of the better shielding on the former type of towers.² From the number of flashovers believed the result of poor shielding, the efficiency of shielding can be estimated as 99.2 per cent for the sus-

pension towers and 96.4 per cent for the strain towers.

The 100 per cent protection experienced on the 220-kv lines during the years of surge-crest-ammeter link recording cannot be interpreted as meaning that the lines are "lightningproof." Line A tripped out in 1933. The grounding on the line has been improved since, but on the basis of 11 years' operation and an estimated 960 strokes, the efficiency of protection is about 99.9 per cent. This record emphasizes the need for long periods of study of well-protected lines, since flashovers occur so seldom that the strokes causing them might be considered freaks. It is evident that some further improved protection will have to be developed if perfection is to be attained.

Discharges Through Lightning Arresters

Surge-crest-ammeter brackets are mounted on 26 banks of lightning arresters and one set of 220-kv expulsion gaps. Table XIII summarizes the records obtained since the first brackets were installed in 1935. It will be noted that 35 of the 53 arrester discharges, or 66 per cent, are less than 1,000 amperes. Only three of the discharges, or six per cent, exceed 2,700 amperes.

Summary

1. The recording of lightning currents with surge-crest-ammeter links began in 1934. In the ensuing years through 1942, 5,501 bracket records have been obtained from transmission towers aggregating 13,227 tower-years of exposure. There have been 54 sets of records from lightning arresters, obtained during 155 bank-years of experience.

Table XIII. Summary of Discharges Through Lightning Arresters

Arrester Type	Period of Record in Stack- or Bank-Years	Discharge (Amperes)	Distribution of Records	
			Number	Per Cent
220-kv one-phase stacks.....	27.....	200.....	2.....	50
		2,100.....	1.....	25
		2,500.....	1.....	25
220-kv one-phase expulsion gaps.....	6.....	9,700.....	1.....	100
132-kv one-phase stacks.....	20.....	600.....	1.....	100
66-kv three-phase banks.....	68.....	1- 500.....	10.....	41.6
		501-1,000.....	6.....	25.0
		1,700-2,000.....	3.....	12.5
		2,200.....	1.....	4.2
		2,600-2,700.....	2.....	8.3
		5,400.....	1.....	4.2
		7,400.....	1.....	4.2
		1- 500.....	13.....	54.1
		600.....	3.....	12.5
		1,050.....	2.....	8.3
66-kv one-phase stacks.....	198.....	2,100-2,400.....	2.....	8.3
		2,600.....	2.....	8.3
		4,500.....	2.....	8.3

2. Based on an eight-year period of record in one case and a five-year period in the other, two similar 220-kv lines running in a generally north-south direction experienced the same average number of strokes per year within approximately seven per cent. Two similar 66-kv lines lying in an east-west direction experienced the same average number of strokes, within about three per cent, during a seven-year period.

3. A 132-kv line, having about the same span lengths as a 220-kv line but lying in a more or less northwest-southeast direction within about two miles of a river throughout its length, experienced on the average about 40 per cent more strokes per unit length than the 220-kv line during an eight-year period.

4. The maximum number of strokes recorded on one of the transmission lines in one year was 4.9 times the minimum number recorded in another year. The maximum number on this line occurred in the same year that the minimum number occurred on a comparable line.

5. The strokes in single years to a line deviated up to 89 per cent from the seven- or eight-year averages. The average number of strokes recorded in two or more consecutive years did not deviate so much as this from the long-time records. With these experience records, it is possible to estimate the long-term experience on a line from the experience of a few years.

6. The number of strokes recorded in single years on a line 92 miles long did not vary so much as those recorded on shorter lines. It may be inferred from this that the number of lightning troubles will not vary so much from year to year on long lines as it will on shorter ones.

7. The data for tower lightning currents show most records in the range from 5,000 to 10,000 amperes with a secondary maximum in the 25,000- to 30,000-ampere range. This suggests that there may be two types of lightning discharges, most of each type producing tower currents in different ranges.

8. The majority of towers were not struck more than once a year, but it is not unusual for a tower to be hit twice in one season. Only one tower during an eight-year period on two lines (5,248 tower years) has been struck three times in one year. More than three strokes per year has not been recorded on any tower under observation.

9. Of 656 towers observed for eight consecutive years, 138, or 21 per cent, did not produce records indicating that they were struck by lightning during the period. Most of the towers (78 per cent) were not struck more than twice during the eight-year period.

10. The maximum number of years in succession that any one tower has been hit is four, and this occurred only three times in eight years. Occasionally a tower is hit two years in succession, but it does not occur often.

11. It may be inferred from the extensive stroke data that the installation of localized lightning protection usually cannot be justified on the basis of a one- or two-year trouble record. The chances are that lightning will not strike the particular location in the years immediately following.

12. Three lightning currents ranging from 3,000 to 45,000 amperes have been recorded on a flagpole. The pole is about 300 feet above street level, and is the highest point within three city blocks.

13. From 104 sets of records obtained from towers with surge-crest-ammeter brackets on all four legs, it is possible to estimate the range in which a tower current lies when only one bracket record is available from a tower. When the single-leg records indicated tower currents of 2,000 amperes or less, the sum of the four leg records was as large as 50 times the single-leg indication. In the range from 2,000 to 70,000 amperes in a tower, the single-leg records usually were not very much in error. In the four cases where the tower current indicated by a single bracket was 76,000 amperes or greater, the sum of the four bracket readings

was appreciably less than the single-bracket indication.

14. There were 25 cases where the surge-crest-ammeter links on a single leg yielded no current record when there was current in the other legs. These records showed tower currents as great as 6,200 amperes when no record was obtained from one of the brackets on that tower.

15. From the four bracket installations it is estimated that 6.4 per cent more strokes were recorded by them than would have been recorded if only one bracket had been installed on those towers.

16. Bonding of adjacent transmission towers appears helpful in reducing footing resistance. It apparently does not cause any appreciable change in the number of disturbances affecting more than one of a group of neighboring towers.

17. Flashovers occurred on 66-kv towers having as many as eight continuous counterpoise conductors. However, the eight-year record of the 132-kv line indicates that a multiple-counterpoise system has prevented flashovers when the ground resistance is ten ohms or less.

18. A single continuous counterpoise seems to provide good protection for 220-kv towers having an insulator flashover level of 1,600 kv or more, provided that this type of grounding brings the footing resistances to less than the flashover value of the insulation in kilovolts divided by 100.

19. The average value of the surge impedance of a conductor in air seems to be less than 235 ohms. This is appreciably less than the theoretical value of 400 or 500 ohms often used. The data on which this estimate is based imply that mid-span clearances on transmission lines may not need to be so great as often are allowed for the prevention of mid-span flashovers.

20. Fairly good predictions of line performance can be made by a relatively simple empirical method.

21. The efficiency of protection of the 220-kv lines is estimated to be about 99.9 per cent. This high efficiency means that strokes causing flashover are so rare that many years may elapse between flashovers. The lowest efficiency of protection exists on one of the 66-kv lines, where it is about 97.5 per cent.

22. It is evident that preventive protection can be made very effective, but it does not attain perfection.

23. The largest recorded current through a lightning arrester was 7,400 amperes occurring in a 66-kv bank. A surge current of 9,700 amperes through a 220-kv expulsion protective gap was recorded.

Table XIV. Estimate of Lightning Outages on Line Section With Overhead Ground Wire

Ranges of Tower-Footing Resistance	Towers in Range		Maximum Safe Current for Towers in Range	Percentage of Tower Currents Exceeding Safe Values	Probability of Flashover
	Number	Per Cent			
0-1	3	8.83	680,000	0	0
1-25	0	0			
26-30	3	8.83	22,700	25	0.022
31-35	2	5.88	19,400	27.5	0.016
36-40	3	8.83	17,000	29	0.026
41-45	5	14.70	15,100	32	0.047
46	1	2.94	14,800	32	0.009
52	1	2.94	13,100	35	0.010
59	1	2.94	11,500	40	0.012
61-65	2	5.88	10,500	45	0.026
66	1	2.94	10,300	46	0.014
75	1	2.94	9,100	60	0.018
81-90	3	8.83	7,600	70	0.062
91-100	0	0			
101-110	2	5.88	6,200	78	0.046
114	1	2.94	6,000	80	0.024
120-125	2	5.88	5,400	82	0.048
151	1	2.94	4,500	86	0.025
305	1	2.94	2,200	95	0.028
355	1	2.94	1,900	97	0.029
Totals	34	100.00			0.46

Appendix. Estimating the Lightning Outages of a Transmission Line

Even a cursory survey of the literature on lightning protection indicates that a large number of factors should be considered theoretically when attempting to predeter-

mine the lightning performance of a line. Some of these factors are:

1. Number of storms per 100 miles, per year
 - (a) Number of strokes.
 - (b) Intensity of individual strokes.
2. Topography.
3. Cloud height.
4. Effective ground plane.
5. Soil resistivity and its variations.
6. Insulation.
7. Coupling factor.
8. Span length.
9. Mid-span clearance between conductors and overhead ground wires.
10. Shielding
 - (a) Number of overhead ground wires.
 - (b) Location of ground wires.
 - (c) Influence of hillsides.
 - (d) Nearby structures.
11. Surge impedances
 - (a) Tower.
 - (b) Overhead ground wires.
 - (c) Grounding system.
12. Effect of method used in measuring ground resistance.
13. Area covered by grounding system.
14. Number and type of grounding electrodes.
15. Lightning current measurements
 - (a) Accuracy of magnetic links.
 - (b) Distribution of current in tower.
16. Wave shape of lightning surge.
17. Movement of conductors by wind
 - (a) Effect on shielding.
 - (b) Effect on clearances.
18. Design features affecting electrostatic field around insulation.
19. Effect of weather conditions on electrostatic field around insulation.
20. Instantaneous value of power voltage at instant of stroke.

Since inclusion of any large number of these factors in a computation is impractical, a method⁴ was developed a few years ago which included only those factors that experience had shown to be most important. Initially the method was applied only to shielded lines, but now it is extended to all lines.

Experience with line *D* before its improvement with shielding and counterpoise afforded an opportunity to test the accuracy of the computations.

Before improvement, the line had a single overhead ground wire installed on end sections only. The computation of estimated flashovers resolved itself into three parts,

one for each of the three types of line sections:

1. Overhead ground-wire section.
2. Towers.
3. Spans between towers without overhead ground wires.

Detailed Calculations

1. At the two ends of the line, there was a total of 4.25 miles of single overhead ground wire. This wire is assumed to provide practically perfect shielding for purposes of calculation. There were 34 towers in the sections having shielding wire. The footing resistances of these towers were distributed as indicated in Table XIV. The line insulation had a flashover level of about 510 kv. The coupling factor between the overhead ground wire and the conductors was about 0.25. The maximum tower potential without flashover is then safe tower potential = $510 / (1 - 0.25) = 680$ kv.

In Table XIV, the maximum safe tower current is obtained for column 4 by dividing 680 kv by the maximum footing resistance in each range from column 1. From Figure 2 is entered in column 5 the percentage of tower currents that can be expected to exceed the given maximum safe value. The probability of outage per stroke for each range of tower-footing resistance is the product of the values in columns 3 and 5 expressed as decimals. The total probability of outage per stroke for the section is 0.46. Since the average strokes per 100 miles of line per year for the entire transmission system is 113 (Table II), the probable outages per year for the overhead ground-wire section is $113(4.25 \text{ miles}/100 \text{ miles}) 0.46 = 2.2$.

2. The section of the line without overhead ground wires was 18.58 miles long, which experienced $(113 \times 18.58) / 100 = 21$ strokes per year. The absence of the overhead ground wire made the coupling factor equal zero and the safe tower potential equal the flashover value of the insulation, which was 510 kv.

It is assumed⁵ that 20 per cent of the strokes to the line hit the towers and the

remaining 80 per cent hit the line conductors. The strokes terminating on the towers are assumed to cause flashover in accordance with probability calculations similar to those made for the overhead ground-wire section. The probable flashovers per year caused by strokes to towers without overhead ground wires come to 3.3.

3. There was an average of about $0.80 \times 21 = 16.8$ strokes each year terminating on line conductors between towers. It has been shown in the paper that the surge impedance of a conductor in air averages less than 235 ohms. On this basis, it can be assumed that the conductors on line *D* could carry more than 510 kv/235 ohms = 2,100 amperes, without flashover. From Figure 2 it is roughly estimated that ten per cent of the strokes to line conductors did not cause flashover. Accordingly, about 90 per cent of the 16.8 strokes that hit the line conductors each year caused flashovers, or 15.1.

A summary of the estimated flashovers on the three types of line sections is as follows:

Towers with overhead ground wires.....	2.2
Towers without overhead ground wires.....	3.3
Spans without overhead ground wires.....	15.1
Estimated tripouts per year.....	20.6

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Supervisory Control for the World's Most Modern Steel Mill

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WARTIME EXPANSION of the Pacific Coast shipbuilding industry has accentuated the need for new steel-producing facilities in the West. Moreover, rich deposits of iron ore, coal, and limestone—the raw materials required to produce steel—are close at hand in the central inland section of the western states.

To meet this need and to take full advantage of raw materials so strategically situated, a completely integrated steel plant has been constructed in that region. In this plant, the largest west of the Mississippi River, approximately 700,000 tons of finished ship plates and 200,000 tons of structural steel will be produced annually for Pacific Coast industry. This production goal required the building of 252 coke ovens, three blast furnaces, nine open-hearth furnaces, a 45-inch slab mill, a 132-inch plate mill, and a 28-inch structural-steel mill. Supplementary units include a sintering plant for treatment of the ore and an exceptionally large central maintenance shop. Adequate outside shop facilities are not available in the region of the plant, thus necessitating self-sufficient shop facilities within the plant.

For the first time in the history of steel-mill design, the entire electric-power supply and distribution system will be under the supervision and control of a centrally located power dispatcher. Particularly significant is the fact that all apparatus in the mill motor rooms likewise will be remotely controlled and unattended.

One of the most comprehensive supervisory control systems yet constructed will permit control of all of the widespread units of this plant from one dispatching center. This is in distinct contrast to the previous practice of maintaining local operators at all substations and local attendants in all mill motor rooms.

Supervisory control is a selective code system designed to provide remote control and supervision of a relatively large number of apparatus units through the medium of a single pair of control wires for each remote station. This system utilizes telephone-type relays throughout, and operates from a battery source of

48 volts direct current. It is simply a means by which remote-station apparatus can be supervised and directed, just as a substation operator is directed by telephone.

General

In designing the electric-power system for a new plant, the steel-mill engineer faces the same problems of generation, transmission, and distribution that confront the central-station engineer. However, in the utilization of this power for the production and processing of steel he is in a field peculiarly his own.

Of utmost importance is the problem of supplying 700 volts direct current for the main drive motors in the slab, plate, and structural-steel mills. Large motor-generator sets are required for this purpose, together with their associated exciter sets, ventilation equipment, and miscellaneous auxiliary apparatus. Particular interest, therefore, is centered in this mill motor-room apparatus and its special control and supervision features.

Up to this time it has been customary practice to provide an attendant in each mill motor room. His function is to control locally all motor-room apparatus. His duties include switching of all primary and secondary distribution circuits for the mill, as well as starting and stopping of all motor-generator sets and associated apparatus. An idea of the labor and time that would be involved in carrying out these duties in this new mill may be gained from the fact that the plate-mill motor room is 65 by 575 feet in area.

The single-line diagram (Figure 4) indicates the magnitude of the power system, which serves a plant area approximately $2\frac{1}{2}$ miles long by one mile wide. Although not shown, a large

number of radial feeders are supplied from the distribution busses indicated for each substation.

Each unit of the project is provided with an entirely independent supervisory-control setup. These units are the open hearth, sintering plant, blast furnace, shop, coke plant, 138-kv tie substation, and the slab, plate, and structural-steel mills. Although all dispatching-office equipments are located at a common point, operations can be performed, or signals received over all equipments independently.

In this application, the electrical dispatcher is also the power-station switchboard operator. The dispatching-office supervisory-control equipment for each unit of the mill is incorporated in the same cubicle which houses the direct-acting control, as well as the metering and protective relaying, for the 13.8-kv feeder circuit supplying that unit.

With the power-supply system for the mills literally at the fingertips of the dispatcher, all motor-room apparatus can be placed in service with an absolute minimum of man power and in a minimum of time. Supervisory control provides immediate notice to the dispatcher of the loss of any normal power source. Standby tie lines between substations and between motor rooms can be switched in with minimum interruption to plant production. Provision is made also for the dispatcher to control system power factor in order to maintain maximum operating efficiency.

Completely automatic control of such motor-room apparatus as motor-generator sets and mercury-arc rectifiers has been available to the industry for many years and has proved itself in service. Coordination of such local automatic control with remote supervisory control makes possible an operating setup based on completely unattended motor rooms. Under normal operating conditions these motor rooms will be locked, and the apparatus therein will be accessible to authorized maintenance personnel only. Likewise, all conventional substation apparatus throughout the project will be unattended and locked in a similar manner.

As in previous mill practice, operators in control pulpits overlooking the slab, plate, and structural-steel mills will control locally all operations involving the handling of steel. With all motor-room apparatus ready to serve the mill, the pulpit operator will receive automatically a visual go-ahead signal, and, through the interlocking of a permissive relay, may proceed with mill operation.

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In the dispatching office, one or more panels are assigned to each station or mill unit under remote control. The control escutcheons are physically laid out in a logical arrangement with a miniature bus system in distinctive colors to indicate all principal busses, feeders, and tie lines. Each escutcheon is a small shield or panel which has assembled on it all of the control keys, push buttons, and indicating lights associated with a given apparatus unit.

Each dispatching equipment incorporates a station-alarm lamp, a "pilot" or "normal" lamp, and a control-line supervision lamp: The pilot lamp is the only

points, with provision for an additional 200 future control points. In general, all 138-kv, 13.8-kv, 6.9-kv, 2.3-kv, and 460-volt 60-cycle circuits, as well as the 250-volt d-c circuits, are controlled by the supervisory-control system. All 13.8-kv circuits in the switchhouse, coke plant, sintering plant, and slab mill are equipped with breakers of 1,000,000 kva interrupting capacity. These are of the air-blast air-operated station type. Elsewhere, feeder reactors permit the use of 500,000-kva interrupting-capacity removable-type breakers. The 250-volt d-c circuits throughout the plant are supplied from ignitron-type rectifiers

The selecting system consists of straight counting codes. In case of a selection initiated by the dispatcher, the desired code is sent to the remote station, where the selected relay returns its code to the office. If the returned code does not agree with that sent out, no further operation is possible. If it does agree, the "check" or point lamp on the individual escutcheon is lighted. For a circuit-breaker operation the dispatcher then turns the twist key to the desired "close" or "trip" position and presses the master-control push button. This action sends the closing or tripping code to the selected unit, causing it to operate. As the breaker changes position, an auxiliary switch causes the new position to be reported to the dispatcher, changing the red and green lamps to correspond.

An automatic operation is reported in a similar fashion. Should a circuit breaker trip automatically, its auxiliary switch causes its selecting code to be transmitted to the office and the alarm bell to notify the dispatcher that some action is required. The office relay returns the check code to the substation, which immediately sends its position code to change the red lamp indication to green. As the dispatcher hears the bell, a glance at his row of panels informs him which substation is involved by the lighting of a station-selection lamp. On the panel reporting the alarm the individual breaker that opened is clearly indicated by the disagreement lamp. The dispatcher may select and reclose the breaker immediately. Should a permanent fault cause the breaker to reopen immediately, he may dispatch his maintenance crew to locate and correct the fault.

Once each week it may be desirable to test the over-all supervising system. The accepted method consists of a "master check," in which the dispatcher presses a master-check push button. This causes a checking code to be transmitted to the remote-control center, which compels each circuit breaker or other operated device to send its present position code to the dispatcher's board. Thus the equipment is given an over-all positive test and, at the same time, assures the dispatcher that all equipment is in good working order.

If automatic-breaker operations occur at the substation during the master-check operation they will be indicated immediately, provided that the master check has progressed beyond their point-assignment number. Otherwise, they will take their proper turn in the point-assignment sequence.

If it should become necessary for the

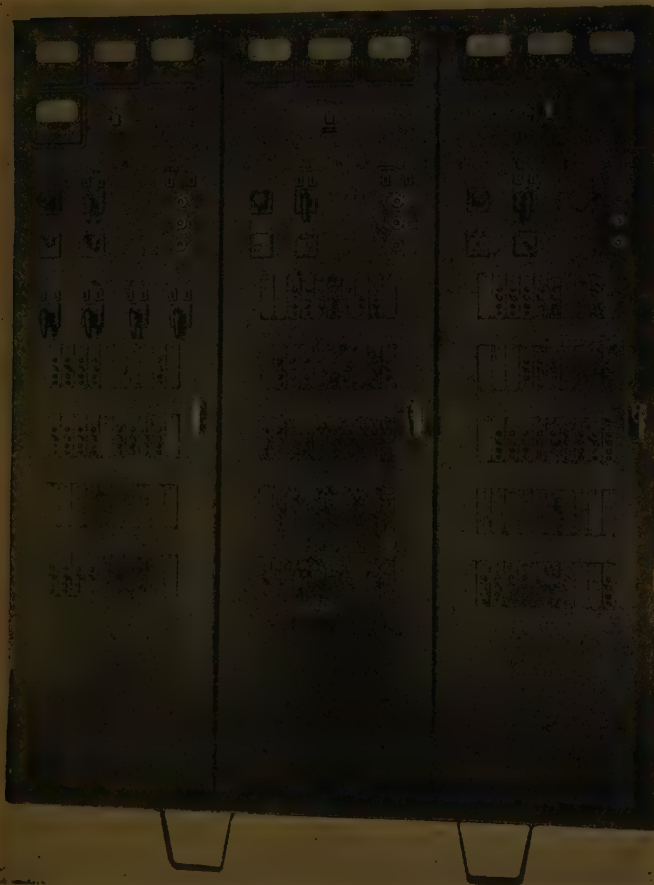


Figure 1. A short section of the dispatching control board

one of the three normally lighted. This indicates that the system is at rest but in a condition to operate. Should a fault occur the alarm bell rings, and a station lamp shows the station from which the signal is coming. A glance at the group of escutcheons locates the individual breaker or protective device which has caused the alarm through the glowing of the disagreement lamp. Thus the dispatcher is able to note quickly what has happened and to restore service by reclosing the necessary breakers.

In this plant, there are 11 control centers and approximately 500 control

with semihigh-speed heavy-duty steel-mill-type circuit interrupters.

Details of Operation

As previously noted, the supervisory-control equipment operates from 24-cell battery circuits. The use of alternating current is undesirable since the control system, which brings vital information to dispatching headquarters during times of trouble, is most important when the a-c supply is off. For each station under remote control only two telephone-type line wires are required.

dispatcher to select and operate any substation device during master check, he may do so. The only special requirement is that he hold the selection key in the depressed position until the point-selection lamp is lighted.

As soon as the desired operation on that point is completed, the master-check operation will be resumed automatically. At the end of the master-check operation the alarm bell will be energized to notify the dispatcher that the check has been completed; he must then depress the "reset" key to silence the alarm.

In periodic testing or for special operations following maintenance work, it is sometimes desirable to operate a breaker several times. In order to save time and eliminate the necessity of reselection, the selection may be retained by holding the master-control push button in the closed position until the red and green indicating lamps have changed position indication. In this way the selection is maintained and, by changing the position of the twist key to the opposite position and again pressing the master-control key, the opposite operation is performed. On the last operation, if the master-control push button is not held in too long, the equipment will reset automatically and become available for any other desired operation.

The supervisory-control equipment is composed of extremely simple, mechanically uniform telephone relays, which send and receive codes at approximately 14 impulses per second. No polarized relays or selector switches are used. The control is fast, positive, and inherently antipumping, and automatically checks each selection. The entire equipment normally is at rest. Continuous individual lamp indications are provided for supervising the position of each remote apparatus unit.

Control by the dispatcher is performed in a manner very similar to that in which an operator in the remote station itself would control the apparatus by means of the usual local control. Coded operation control provides protection against the possibility of false operation of any apparatus unit due to foreign voltages on the line wires that might be caused by surges from nearby power lines or lightning.

Transfer Switches

At all remote locations any apparatus unit can be transferred at any time from remote to local control by means of local transfer switches. Remote supervision of the positions of these transfer switches is

provided by voltage groups. In addition, each group of transfer switches also controls a corresponding indicating lamp installed over the substation or motor-room door. This lamp is lighted when any one of the group of transfer switches is turned to the local-control position. Thus it serves as a warning to a maintenance or test engineer about to leave the station, should he unintentionally leave one or more transfer switches in the local-control position. As a safety precaution, any apparatus unit may be tripped by local control at any time, regardless of the position of its transfer switch. The dispatcher retains supervision of positions of all apparatus units, even though they may be under local control.

Control Lines

Each pair of control lines is supervised continuously to detect open-circuit or short-circuit conditions. Each such channel is used also for telephone communication with its associated station, without interfering with supervisory-control operations. This communication feature

permits the dispatcher to keep in contact with maintenance men at any station.

Should a short circuit or an open circuit develop in a control line, the alarm will sound, the "normal" lamp will be de-energized, and the line-supervision lamp will be lighted. Depressing the "reset" key will silence the alarm, but the "normal" lamp will remain de-energized and the line-supervision lamp will remain lighted until the line trouble is corrected and the "reset" key is depressed again.

If any substation-apparatus units have changed position during this time, the alarm will sound again as the "reset" key is depressed, and all changes then will be so indicated automatically and in numerical sequence.

Supervisory Versus Direct-Wire Control

Although the distances between the dispatching office and the remote-control stations are relatively short, the large number of operations required at each station fully justifies the supervisory-control system. The use of a single pair



Figure 2. Dispatching-office supervisory-control cubicle, with open doors showing flush-mounted relay cases on inside panel

of wires to each remote station, as contrasted with direct-wire control, represents a major saving in copper that is so essential in today's conservation program.

The use of supervisory control has many operating advantages over any direct-wire control scheme. Supervisory control requires a minimum of space and readily accommodates future additions. Line troubles are reduced to a minimum, and the line wires are supervised continuously for open circuits and short circuits. Protection from induced voltages, or contact with power lines, is simpler to provide than with direct-wire control. Supervisory control also accommodates voice communication.

Motor-Room Control

Each mill motor-room has an oil-cellar in which are located the various oil pumping systems for the bearings of the rotating apparatus within the motor room. These oil cellars are accessible from the outside of the motor room, and will be under the care of an attendant.

Because of the need for heating of the lubricating oils under certain conditions and the intricacy of the system of valves required, it was not considered feasible to place the oil-cellar equipment under supervisory control.

No action will be taken toward starting of the motor-room equipment until the oil-cellar attendant reports all oiling systems ready for operation.

Preparatory to starting the main motor-generator sets, the dispatcher will disconnect all space heaters. These heaters prevent moisture condensation on the machine windings during shutdown. Next he will start all fans and auxiliary exciter sets.

He then will start the flywheel motor-generator set, which will accelerate automatically under slip-regulator control. After the unit reaches normal speed at no load, a relay is energized which notifies the dispatcher that the set is ready for mill operation. This relay also sets up a permissive circuit to the control pulpit in the mill and lights a lamp which indicates to the mill operator that the mill is ready for his control.

The synchronous motor-generator sets in the plate and structural-steel mills also are started by the dispatcher, and will accelerate under automatic control. Reactor starting is utilized for these sets. Having reached maximum speed with the reactor in circuit, the field is applied automatically to bring the motor up to synchronous speed. At this point the start-

ing reactor automatically is short-circuited. Through an interlock on the field switch the dispatcher is notified that the set is up to speed.

In case protective devices indicate approaching trouble, such as overheated bearings, the pulpit operator may clear his rolls of steel before the affected power-supply units are shut down.

Local interlocking is provided in each mill motor room to insure against apparatus units being started in any but the proper sequence. A synchronous or flywheel motor-generator set cannot be started until its associated exciter sets are in operation. The flywheel set, which is equipped with a wound-rotor driving motor, cannot be started unless its liquid slip regulator is in the resistance-all-in



Figure 3. Typical supervisory-control relay and control-escutcheon assembly

position. Furthermore, dynamic braking of this same set cannot be applied unless the regulator is again in the resistance-all-in position and the motor primary breaker is open.

Regulator Control for the Structural-Steel Mill

The synchronous motor-generator set for the structural mill is equipped with an automatic power-factor or reactive-kilovolt-ampere regulator, which can be cut into and out of service by supervisory control. A similar regulator is provided for the two synchronous motor-generator sets in the plate mill. The dispatcher is provided with supervision of the latter regulator; that is, he has indication of whether or not it is in service, but he cannot control it.

With all mills operating normally, the plate-mill synchronous motor-generator sets will be under automatic-regulator

control. The structural-steel-mill regulator will be cut out of service, and the synchronous unit will operate at a fixed full-load excitation value.

When the plate-mill regulator is cut out of service (by manual control at the regulator), then the structural-steel-mill regulator should be cut into service. If the plate-mill synchronous units are operated without regulator control, their excitation also will be set at the full-load value.

No-Alarm Feature

To complete his picture of operating conditions in the mills, the dispatcher is provided with supervision but not control of certain apparatus units directly controlled by the mill operator. This group includes such units as the scale breaker, the spreader, the edger, and the d-c breakers on the flywheel and synchronous motor-generator sets.

These units may be started and stopped, or the d-c breakers closed and opened, frequently during normal mill operation. To avoid unnecessary annoyance to the dispatcher, the associated changes in supervisory-lamp indications are not accompanied by an audible alarm, as is the case on other supervision points.

Miscellaneous Supervision Features

Continuity of power supply to all busses in all stations is supervised continuously through the medium of bus-voltage relays. This feature indicates whether or not a given bus is energized, but does not indicate the actual bus voltage. Operation of any station annunciator is reported immediately by supervisory control.

Rectifier Control

In placing a rectifier in service by supervisory control, the dispatcher must first close the a-c breaker and then the positive and negative d-c breakers. Electrical interlocking is provided to prevent the reverse sequence of operation.

Shutdown of a rectifier may be accomplished by tripping the a-c breaker, which in turn will automatically trip the d-c breakers through electrical interlocking. If desired, the d-c breakers and then the a-c breaker may be tripped independently, in that sequence.

Closing and tripping of both the positive and negative d-c breakers for a given rectifier are combined on the same supervisory control point. Supervision of the

GEOGRAPHICAL LAYOUT (APPROXIMATE)

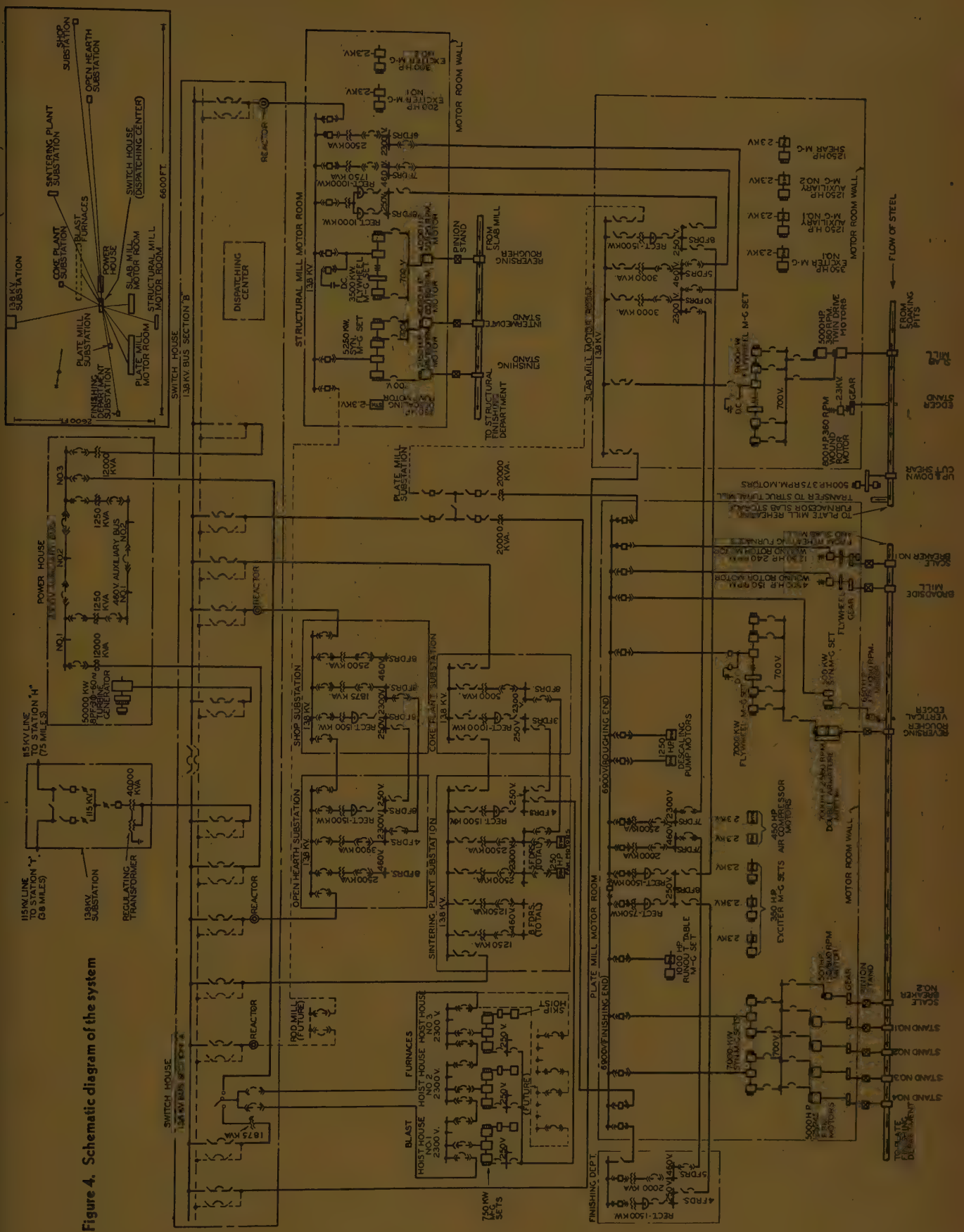


Figure 4. Schematic diagram of the system

position of each such pair of breakers is obtained through two interlock contacts in series (one on each breaker), to insure that both breakers are closed when so indicated.

Rectifier Protection

Causes of shutdown of rectifiers are segregated into two groups. If shutdown is due to a temporary condition such as overload or reverse current, the unit may be restored to service safely by the dispatcher as soon as the protective-relay equipment will permit. (A very heavy short-time overload will be detected by induction-type a-c overload relays, and a continuous overload condition of lower value by the thermal device on the rectifier transformer.) This type of shutdown will be indicated by tripping of the a-c and d-c breakers.

On the other hand, shutdown resulting from loss of the rectifier-cooling water supply or from excess temperature of a rectifier tank or mercury-vapor pump probably will necessitate the attention of the maintenance engineer. This type of shutdown will be indicated by operation of the rectifier annunciator alarm, as well as by tripping of the a-c and d-c breakers. Thus the dispatcher can determine his course of action accordingly.

Step-Regulator Control

Control of the step-type regulating transformer bank at the tie station to the utility company is also under the dispatcher. Tap position may be checked at any time, and is indicated simultaneously with control of the tap-changing mechanism. A local "on position" indicating lamp is provided at the substation to indicate that the regulator is on a definite tap position at any given time. The lamp indication is duplicated on the dispatcher's escutcheon for this regulator control.

Tie Substation Alarm Features

In recognition of the importance of the 40,000-kva transformer bank which serves as a tie between the utility power system and the mill, operation of all associated

alarm devices is reported by supervisory control. Individual supervision is provided for pressure alarm, oil-level alarm, oil-temperature alarm, and an alarm upon starting of the blowers, by automatic control.

A similar alarm is given also for low air pressure in the supply system for the pneumatically operated 138-kv oil circuit breakers in the tie substation.

Pilot Channel Supervision

Pilot-wire relaying is utilized to protect the several sections of a loop-type power supply for the blast furnaces. The pilot-wire channel for each of these sections is supervised continuously by the type of auxiliary relays customarily used to detect short circuits, open circuits, and grounds. The alarm contacts of these relays operate through the supervisory-control system to warn the dispatcher, so that he may promptly institute corrective action if trouble should develop.

Door-Lock Supervision

All remote stations and mill motor rooms are normally unattended and the entrance doors are locked. The dispatcher is provided with continuous supervision of each of these door locks. A special contact is actuated by the door-lock mechanism, and is independent of the actual door position. Thus, once the door is unlocked, maintenance men may go in and out without actuating the alarm.

Maintenance men will be required to check in with the dispatcher by telephone when entering a remote station, and again when they are ready to leave. The door-lock supervision feature provides a final check to make certain the station door is left locked.

Blackout

Supervisory control also provides a vital wartime feature in that the dispatcher can institute a complete blackout on a moment's notice. In general, only external lighting will need to be switched off for this purpose, as all principal units of the project are of windowless construction.

Operative Burden

At first thought, the operation of such a system as this by a single dispatcher would appear to be placing too much burden on one operator. However, once the power system is in service, system changes will be relatively infrequent. Troubles will occur, as on any system, but they should be isolated in nature. Moreover, troubles at any point on the system can be recognized immediately and prompt corrective action taken.

Ample notice will be given when starting up any of the mills. Several hours' time normally is allowed in which to place in service all rotating apparatus in a given mill motor room preparatory to rolling steel.

Conclusion

Although such equipment is a comparative newcomer to the steel industry, supervisory control has served the central-station industry since 1921. The original installation is still in daily operation. Its basic soundness is well illustrated by the fact that the same type of relays and the same fundamental principles of circuit design are still in use today.

No part of the supervisory control for this plant is new in design. Furthermore, its application to switching operations in the substations throughout this project is entirely conventional. Only the application to motor-room motor-generator sets and associated apparatus is new.

Man-power shortage is particularly critical at this time in the field of technically trained and experienced steel-mill power-system operators. Thus an estimated 80 per cent saving in such man-power for this project, effected by the use of centralized control, represents a vital contribution to the war effort.

Centralized control has required coordinated planning and uniform practices throughout the project. With so many engineering firms involved in the design and construction of the many mill units, this is a matter of utmost importance. As the most comprehensive system of supervisory control yet applied to a major steel mill, this installation will point the way for future installations within the steel industry.

Present D-C Aircraft Electric-Supply Systems

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THE multigenerator aircraft d-c electric system represents an important type which has proved its practicability under military-combat conditions. Proper parallel operation is maintained during extreme conditions of unequal generator speeds and accelerations by using an old but heretofore little-used method, which was first suggested and demonstrated for this application by L. W. Thompson. The successful parallel operation, therefore—the reliability and flexibility of the electric-supply system—is made possible chiefly by the use of voltage regulators, which provide for load division as well as voltage constancy. It was natural that difficulties initially experienced in service were not always clearly understood, and that the equipment and installation in the early stages did not have characteristics which would allow the system to operate with its greatest capabilities.¹ However, with experience and study the causes of these difficulties were determined and remedial measures taken. These changes, although only minor individually, when put into effect collectively, made for a considerable improvement in system performance. The result has been a more reliable system requiring less attention from the crew—a factor of paramount importance for a military plane. This

improved reliability in turn contributes to the assignment of more functions to the electric system.

The development and refinement of the system and its control are truly a product of World War II, realized and continually improved through the co-operative effort of Army, Navy, and manufacturers' engineers. It seems appropriate that some of the problems associated with this unique type of system be discussed at this time, so that its inherent characteristics will be better understood. This paper deals with the type of system at present used by the multiengine Army type of plane. However, results can also be interpreted for the Navy type of d-c system. The emphasis of the paper is primarily upon the performance of the present system and not on developments now in progress, some of which have been or are being discussed in other papers. This paper is devoted to details of performance, the significance of which has been enhanced, not only by present military use, but by the possible adoption of a similar system for commercial aviation in the postwar period and for d-c systems more generally.

A schematic diagram of the type of aircraft electric system discussed in this paper is shown in Figure 1. An aircraft generator is connected directly to each of the four engines on the airplane. Proper parallel operation is obtained by applying a drop of 0.5 volt at full load in each of the generator negative leads to a circuit consisting of equalizer windings in the regulators. A remote-control relay which opens on the flow of reverse current provides generator switching control.

A brief summary of six of the important system problems investigated includes load division, system-voltage accuracy, reverse-current relay-contactor chatter, heavy transient loads, generator-output

capacity, and short-circuit currents. Following this summary each of these problems is discussed more completely.

Load Division

Load division has been found to be affected by two major factors. These are circuit installation and regulator accuracy.

The first, which is primarily the airplane manufacturer's responsibility, requires

(a). That the total negative lead resistance, between the points where the equalizer-coil connections are made, be equal between generators.

(b). That there be no appreciable contact drop (nonlinear resistance) between points in the negative leads where the equalizer connections are made.

(c). That the resistance of the common lead for the field circuit and regulator coil of the regulator be small.

Voltage-regulator accuracy, that is, ability to hold voltage under all load, engine-speed, temperature, and vibration conditions, is important for proper load division. The attention given this problem by the regulator manufacturers is resulting in continued improvements in regulator accuracy.

System-Voltage Accuracy

The necessity for accurate bus voltage is determined chiefly by the battery characteristics which allow for some variation. The load voltage is determined by the voltage regulators.^{2,3} It has been the practice for Army multiengine planes using up to four generators to have the equalizer coil of a disconnected generator left connected, resulting in a reduction in bus voltage. This reduction depends upon the number of generators disconnected compared to those left connected. The reduction in voltage can be avoided by providing manual means to disconnect the equalizer coils of the disconnected generators.

Another factor which has produced large variations in bus voltage has been the continued attempts of the operators to balance the loads by adjustment of the voltage regulators when improper plane circuit installation inherently would not

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allow for accurate load division for all conditions with one setting of the regulators.

Transients due to starting turrets, landing-gear motors, and so forth are appreciable and may result in instantaneous voltage dips of 30 per cent or more. Equipment essential to flight and combat should be made as insensitive to such voltage variations as is practicable.

Relay-Contactor Chatter

Relay-contactor chatter results from

- Parallel operation at light load.
- Generators with a rising-regulation characteristic (overcompounded).
- Relay contactors having reverse-current drop-out settings which are too low.

Contactors with light system load probably cannot be entirely avoided.

to be from 0 to 10 amperes with a pickup voltage of 26 to 27 volts. This inherently resulted in chatter under light-system-load conditions. The reverse-current drop-out band was increased to a band of 8 to 20 amperes reverse current with 27.5 volts on the pickup coil.

With steps made to improve circuit installation, voltage-regulator accuracy, relay-contactor accuracy, generator characteristics, and, to increase relay drop-out settings, relay chatter was greatly reduced as a serious problem.

Heavy Transient Loads

The turret motor Amplidyne or generator sets require some of the largest inrush currents of any equipment on the airplane. It is important, therefore, that the electric supply system have sufficient electrical stiffness to support the bus voltage when the turret motor sets are

have a very important function in helping to support the bus voltage for the shock loads incident to turret starting.

Generator-Output Capacity

Two major factors affect generator output capacity:

1. Generator design.
2. Regulator design and circuit installation.

The first is determined among other design factors primarily by whether the generator is compensated or uncompensated. The second factor is determined primarily by field-circuit resistance, which includes field leads in the airplane and the regulator minimum resistance. The output capacity of a generator may be reduced very materially by generators of uncompensated design having appreciable field-circuit resistance caused by long field leads and the use of regulators having high minimum resistance. On the other hand, the load-output capacity of a generator may be very materially improved by using generators of compensated design and regulators having low minimum-field resistance. The compensated generator was first proposed and demonstrated for this application by S. R. Bergman.⁴

Short-Circuit Currents

The modern four-engine airplane with three batteries is capable of producing total instantaneous short-circuit currents approaching 5,000 amperes. It appears, therefore, that the reverse-current contactors, which were originally specified for interruption of currents of 500 amperes and more recently improved for rated interruption of current up to 2,400 amperes, are not entirely adequate for short-circuit protection. Additional protection

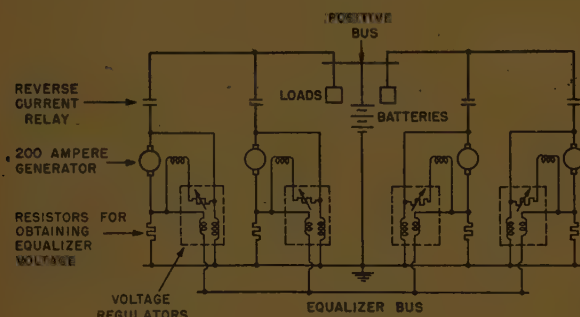


Figure 1. Schematic diagram of typical four-generator aircraft electric-supply system

However, with improvements in the factors which affect load division, the relay contactor chatter at light load has been reduced materially.

A severe type of contactor chatter can be obtained from a generator which has a rising-load-regulation characteristic. Such a regulation characteristic will also tend to produce instability of voltage regulation during parallel operation. Manufacturers, in their design of aircraft generators, have been careful not to obtain a rising-voltage-regulation characteristic for any part of the speed and load range over which the generator must operate. This becomes a prime design factor and must be given proper attention both in design and production testing in order that the generators will not have such a characteristic. If the generator brushes are rotated against rotation, a generator although properly designed in this respect may have a rising characteristic such as to cause severe contactor chatter. Therefore, it is important for this reason also that the generator brushes be properly set and fixed.

Reverse-current drop-out settings of the contactors had been initially specified

started. The stiffness of the electric system is increased by the number of batteries, number of generators, and high generator speeds at the time the turrets are started, while the required amount of electrical stiffness is determined by the amount of starting current required. It was found that the number of batteries greatly affected the amount of starting current that could be made available. This is particularly true if it is necessary to start the turrets with some of the available generators disconnected. Accordingly, it appears that the batteries

Figure 2. Regulation characteristics of 200-ampere compensated aircraft generator

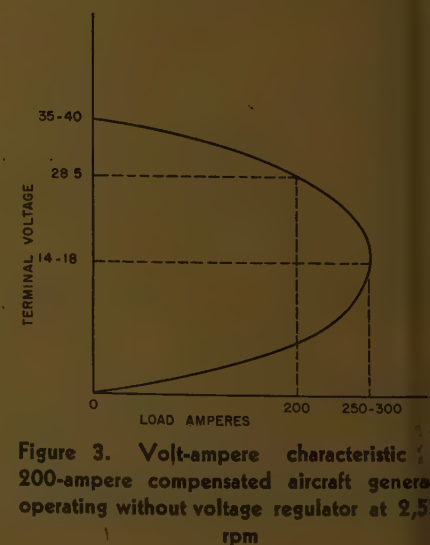
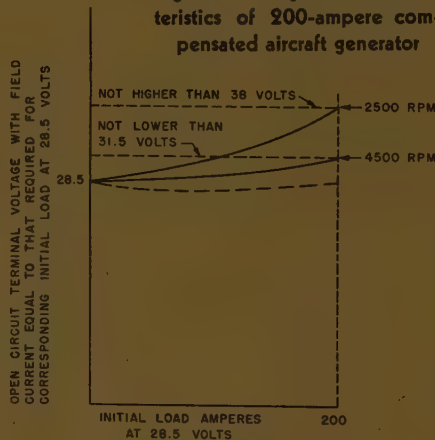


Figure 3. Volt-ampere characteristic of 200-ampere compensated aircraft generator operating without voltage regulator at 2,500 rpm

tion is desirable, since complete re-
lance cannot be placed on all faults to
urn themselves clear⁵ without ap-
reciable damage. Accordingly, con-
sideration is being given to proper cir-
cuit-breaker protection and contactors
of higher interrupting rating.⁶ Reverse-
current circuit breakers provide an ef-
fective method of protecting the vital
generation and battery supply currents.

Conclusions

Considerable improvement in the oper-
ation and performance of the present
type of electric-supply systems for air-
craft has been and can be further re-
alized by

Improvements in the circuit installation.
Continued refinements in the generator,
regulator, and reverse-current relay-con-
tactor characteristics.

The use of compensated generators, regu-
lators with low minimum resistance, and
circuit installation using low-resistance field
leads.

The use of directional protective break-
ers or switches in the battery and generator
circuits.

Aircraft D-C Generator Characteristics

(a). GENERATOR-REGULATION CHARACTERISTICS

Since the generator-regulation char-
acteristic depends to a great extent on
brush setting, it is important that
brushes be set correctly in order to avoid
a rising characteristic which may result
in instability in parallel operation and
severe contactor chatter (also possible
instability when connected to a battery).
Rotation of the brushes in a direction
opposite to machine rotation tends to
produce a rising characteristic.

Figure 2 illustrates a typical regulation
characteristic as determined by labora-
tory tests on a compensated 200-ampere

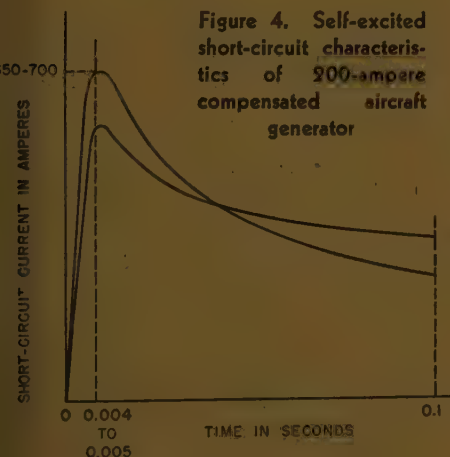


Figure 4. Self-excited short-circuit characteristics of 200-ampere compensated aircraft generator

aircraft generator, at 2,500 and 4,500 rpm. The ordinate is the open-circuit terminal voltage obtained with field current required for the load indicated on the abscissas at 28.5 volts. This voltage, therefore, corresponds to the machine internal voltage for the given load condition. If the curves are as shown by the full lines of Figure 2, the generator is said to have a drooping characteristic at all loads, that is, the terminal voltage drops with increase in load at constant field current. If a generator has a characteristic as shown by the dotted line, it has a rising characteristic at light load; that is, the terminal voltage rises with increase in load at constant field current. Such a generator may cause severe contactor chatter, resulting in failure of the contactor, and also cause instability in parallel operation during light loads.

(b). SELF-EXCITED GENERATOR VOLT-AMPERE CHARACTERISTIC

Figure 3 illustrates the general shape of the volt-ampere characteristic for a self-excited d-c generator operating without a voltage regulator. The field resistance is held constant at a value which gives approximately rated current at rated terminal voltage. The maximum current available depends on generator speed, excitation, brush setting, temperature, and commutation limitations.

At a generator speed of 4,500 rpm, it has been found that the volt-ampere characteristic has about the same shape and proportions as that for 2,500 rpm, when the field rheostat is set for rated load at rated terminal voltage. When a voltage regulator is used, however, the

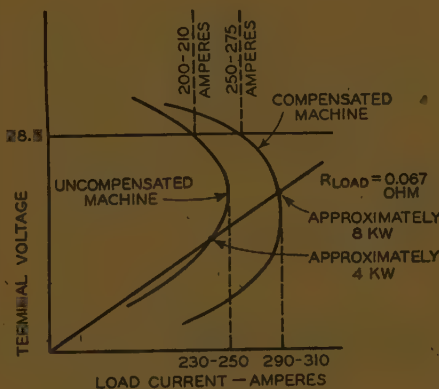


Figure 5. Comparison of volt-ampere characteristics for compensated and uncompensated aircraft generators operating at 2,500 rpm with $r_{fe} = 0.25$ ohm
 r_{fe} = field-circuit resistance external to field

maximum current at high speed exceeds that at low speeds because of the lower excitation requirements at higher speeds.

(c). SELF-EXCITED SHORT-CIRCUIT CHARACTERISTIC

Because of the relatively fast time constant of the armature circuit, the generator short-circuit current rises rapidly to its maximum value and decays to a sustained value at a rate determined principally by the time constant of the generator field circuit.

For a given generator speed and excitation, the maximum initial value of short-circuit current occurs for a dead short circuit at the generator terminals. This, however, does not give rise to the maximum value of sustained current. The fault resistance which will result in the largest value of sustained current may be determined from the generator volt-ampere characteristic.

A typical 200-ampere generator short-circuit characteristic as obtained with an oscillograph is shown in Figure 4. Specific values indicated on the curve are characteristic of a compensated 200-ampere aircraft generator operating at full load previous to the short circuit. If the generator is assumed to supply full load at rated voltage before the application of the fault, the initial value of the short-circuit current is practically independent of the generator speed.

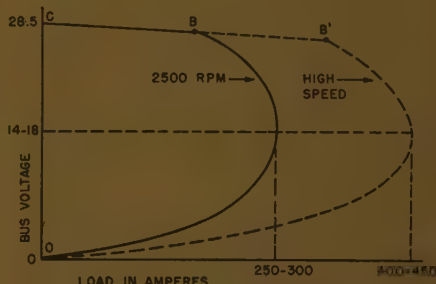


Figure 6. Volt-ampere characteristic of 200-ampere compensated aircraft generator operating with voltage regulator

The sustained value of short-circuit current depends on the fault resistance, the generator speed, and the operation of the voltage regulator. The sustained current may be increased appreciably by operation of the voltage regulator; in fact, for relatively high values of fault resistance and generator speeds, it is possible for the sustained short-circuit current to exceed the initial value.

(d). COMPENSATION AND ITS EFFECTS ON GENERATOR PERFORMANCE

D-c aircraft generators must have a drooping load-regulation characteristic to

allow for stable operation under voltage-regulator control and to minimize relay-contactor chatter. On the other hand, a generator with a large droop will not be capable of as great an output under heavy-overload conditions. One of the most efficient ways of controlling the amount of droop is by the use of compensating windings. This has several very desirable effects.

1. Under emergency-overload conditions, the generator is capable of sustaining a much greater load than would be the case if it were uncompensated. This is of value under sudden-transient-load conditions, particularly when some of the generator capacity (on a multigenerator system) is disconnected. Also the use of compensated generators allows for the starting of higher starting-current loads and results in higher starting torque and greater acceleration of the load. This may be evaluated also in terms of obtaining better performance under emergency conditions with a reduced number of generators or batteries. Both of these are important from the standpoint of weight and reliability of operation.
2. The compensated machine allows for better commutation at higher loads and under short-circuit conditions. The proper short-circuit protection of an airplane makes it desirable that, with the occurrence of a system short circuit, none of the generators' commutators flash over.
3. A compensated machine, because of its reduced requirement for change in field current under overload conditions, is not affected so adversely as the uncompensated machine for high field-circuit resistance associated with long field leads or with regulators having high minimum-field resistance.
4. The compensated machine as compared with the uncompensated machine can be made to have a greater current output at the very low voltages, those associated with system short circuit, or very heavy overloads, which allows for more positive selectivity and simplicity of the short-circuit protective equipment.

It is a primary system-design characteristic for multiengine airplanes to provide an amount of generator compen-

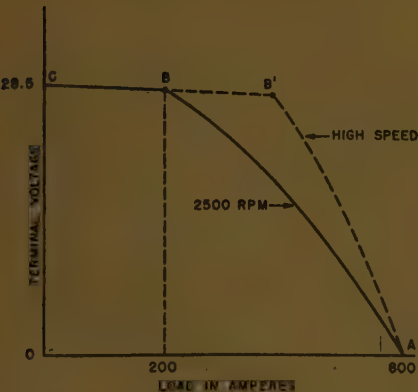


Figure 7. Volt-ampere characteristic of 200-ampere compensated aircraft generator operating with voltage regulator and battery

sation in order to obtain the maximum output of the generators under all system-operating conditions and at the same time to allow for proper stable parallel operation under regulator control. Both generators and regulators can be so designed to meet the optimum-system-performance characteristics desired.

The general shapes of the volt-ampere characteristics for compensated and uncompensated machines of the same rating are shown in Figure 5. It will be noted

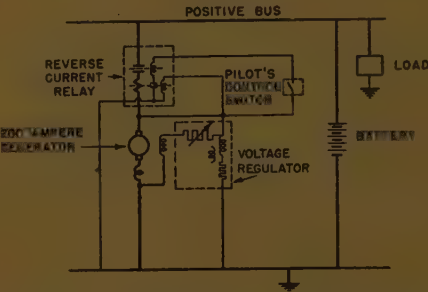
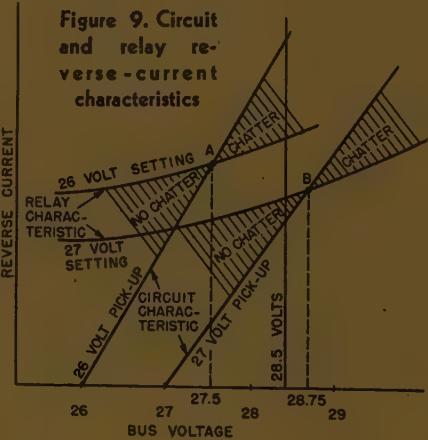


Figure 8. Connections of single-generator aircraft electric-supply system



that the difference in peak current for the uncompensated and compensated machines is about 60 amperes. For a constant resistance load of 0.067 ohm, as shown in Figure 5, the compensated machine will deliver approximately eight kilowatts, while the uncompensated machine will deliver approximately four kilowatts.

Characteristics of Aircraft Generator With Voltage Regulator

Because of the wide ranges in speed and load to which an aircraft generator must be subjected and the different types and ratings of generators which may be used, a voltage regulator with a relatively large range of resistance must be employed.

The field resistance of the generator is varied by a direct-acting voltage regu-

lator,^{2,3} which controls only after the terminal voltage has reached the lower limit of the regulator setting, about 28 volts. The regulator has a magnetic circuit energized by a winding through a diluting resistor from the voltage of the generator being regulated. The force set up by the magnetic circuit is balanced against an adjustable calibrating spring. A second winding on the regulator is used to accomplish load equalization during the parallel operation of two or more generators.

When the generator is operated with a voltage regulator, the volt-ampere characteristic is similar to that shown in Figure 6. Curve CBO is for the base speed of the generator, 2,500 rpm. Curve CB'O is for a higher generator speed.

The portions of the curves CB and CB' may have a slight droop caused by resistance drop between the bus and the point at which the voltage is being regulated. At points B and B', the voltage regulator becomes essentially inoperative, having reduced its variable resistance to a minimum value. When a compression type of regulator is used, the minimum value of regulator resistance is not absolutely constant but is a function of the generator's terminal voltage. The parts of the curves BO and B'O, then, correspond to minimum field resistance. The value of load at which the regulator becomes inoperative increases with increasing generator speed because of the reduced excitation requirements.

Characteristics of a System Consisting of One Generator With Voltage Regulator, Reverse-Current Relay, and One Battery

(a). VOLT-AMPERE CHARACTERISTICS

When a 24-volt battery is added to the system, the volt-ampere characteristic is similar to that shown in Figure 7. At a value of load corresponding to point B or B', depending on the speed, the voltage regulators become essentially inoperative, having reduced the variable field resistances to minimum values.

Table I		
Number of Generators in the System	Number of Generators Out of Service	System Voltage Drop Due to Dead Equalizers
2	1	2.2
4	1	1.1
	2	2.2
	3	3.3
6	1	0.73
	2	1.46
	3	2.2
	4	2.93
	5	3.67

Point *A* represents the battery short-circuit current, in this case 800 amperes.

The battery tends to produce a "stiffer" system than would be obtained with a generator alone; this factor is especially important in supplying heavy shock loads such as motor starting. Since the ampere-hour rating of aircraft batteries is quite small, however, it is not intended that they be called upon to supply heavy continuous loads.

(b). REVERSE-CURRENT-RELAY CHARACTERISTICS

Generator switching control is obtained by means of an automatic relay which is set to close at a predetermined generator voltage and will open upon the flow of current from the battery to the generator.^{2,3} The reverse-current relay consists of a pilot relay and contactor mounted on the same base. The calibration for pickup voltage is made by adjusting the spring tension on the pilot relay. A heavy coil mounted on the pilot relay carries the generator current and opens the relay when the flow of current reaches a preset value in a reverse direction. When the pilot relay closes, the main contactor coil is energized, and the contactor closes, connecting the generator to the bus. Figure 8 shows the connections of the generator regulator and relay and their associated circuits.

Normally the relay is set to close between 26 and 27 volts. As the generator comes up to speed with the pilot's control switch closed, the terminal voltage reaches a value equal to the pickup voltage of the relay, and the relay closes. The bus voltage, if other generators are on the bus, is normally 28.5 volts, which will cause a current to flow in a reverse direction through the relay. Hence, there is a possibility of obtaining enough reverse current to open the relay, after which it will again close because of the voltage impressed upon it. These operations continue, and the relay chatters. This condition may cause a substantial shortening of the relay life. Figure 9 shows how this condition is materially improved by raising the reverse-current drop-out value or the pickup voltage.

In Figure 9, the curves marked "relay characteristic" indicate the amount of reverse current necessary to open the relay at a given bus voltage (or relay-coil voltage) for two relay pickup adjustments. The "circuit-characteristic" curves show the amount of reverse current which the circuit will deliver at a given bus voltage when the relay pickup voltage is less than the bus voltage.

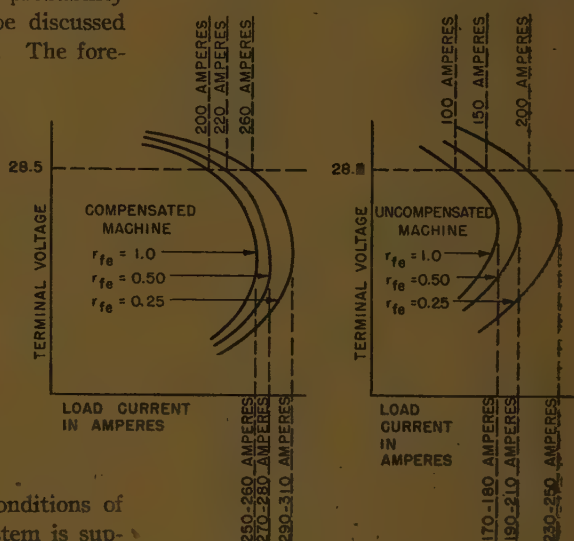
For the particular relay characteristics

shown in Figure 9, the relay will not chatter when set to pick up at 26 volts so long as the bus voltage before closing is less than 27.5 volts. If the relay is set to pick up at 27 volts, it will not chatter so long as the bus voltage before closing is less than 28.75 volts.

In normal operation there is a possibility that a relay set at 26 volts will be made to close on a bus of 28.5 volts. If the relay had characteristics as shown in Figure 9, it would chatter badly if the pickup voltage were set below 27 volts. However, if the point *A* were made to be to the right of the ordinate erected at 28.5 volts, the relay would not chatter. With higher reverse-current drop-out values the intersection *A* can be moved farther to the right, and the probability for relay chatter of the type discussed can be considerably reduced. The fore-

Figure 10. Effect of field-circuit resistance on compensated and uncompensated 200-ampere aircraft generators operating at 2,500 rpm

r_{fe} = field-circuit resistance external to field winding



going analysis applies for conditions of very light loads. If the system is supplying some load, the probability of this type of chatter is greatly reduced, since the equalizer winding in the regulator of the incoming generator will become effective in loading the generator.

If a generator has a rising voltage characteristic (series cumulative field effect) the circuit reverse-current characteristic will be steeper, and the relay will have a greater tendency to chatter, because it takes much less voltage difference between the terminal voltage and the open-circuit bus voltage to produce a large amount of reverse current. (The intersection *A* on Figure 9 would be farther to the left of the 28.5-volt ordinate.) Relay chatter due to this cause, therefore, cannot be avoided unless the incremental generator regulation is drooping.

Another cause of relay chatter is parallel operation with very light loads on the system, aggravated by voltage-regulator inaccuracies and unequal paralleling resistors in the negative leads of the generators. Under these conditions different voltage-regulator adjustments are required to balance the generator currents

at each loading. Accordingly, if the regulators are adjusted for load balance at an appreciable system load, they will be unbalanced at other loads. At light load this unbalance may result in sufficient reverse current in some generators to cause relay chatter. Proper operation requires that the paralleling resistors in the generator negative leads be equal.

(c). EFFECT OF FIELD-CIRCUIT RESISTANCE

As would be expected, the maximum output of a self-excited d-c generator for aircraft is determined to a considerable extent by the field-circuit resistance external to the field itself. Figure 10 shows the effect of resistance external to the fields of a compensated 200-ampere

generator and an uncompensated 200-ampere generator. Values given in this figure are indicative of orders of magnitude. These characteristics show the reduction in maximum output caused by r_{fe} , the field-circuit resistance external to the field winding. It is important, therefore, in evaluating regulator performance, to determine the minimum resistance of which the regulator may be capable when operating with a given generator.

Not only is the output of the generator reduced for higher values of field-circuit resistance, but with a 0.75-ohm increase in the field-circuit resistance, the minimum generator speed at which the regulator begins to control is increased by about 120 rpm when the regulator is set for 28.5 volts. Increasing the minimum-field resistance by 0.75 ohm increases the generator speed at which the reverse-current relay picks up by about 150 rpm with a 26-volt pickup setting of the relay. These values are representative of a system using generators having 2 to 3 ohms field resistance.

(d). GENERATOR COOLING

Insufficient cooling of generators will have a pronounced effect on their maximum output, from the standpoint of increased field resistance, as well as from the standpoint of increased armature resistance. When the generators are operating at full load at a low to medium speed, the regulators are inserting very little resistance into the field circuit. The field-circuit resistance is then largely the resistance of the field itself. In reference to Figure 10, it can be seen that an increase of 0.1 ohm in the

where they can be readily adjusted. Relays are generally installed close to the engine-driven generators in the nacelles. Batteries connected to the main d-c bus are located in the fuselage.

(b). PARALLEL OPERATION AND LOAD
DIVISION

1. *Unbalances Due to Circuit Installation.* In reference to Figure 11, an elementary sketch of a four-engine airplane electrical system assumed to be symmetrical about the load, R_1 and R_2 are positive-lead resistances; R_3 and R_4

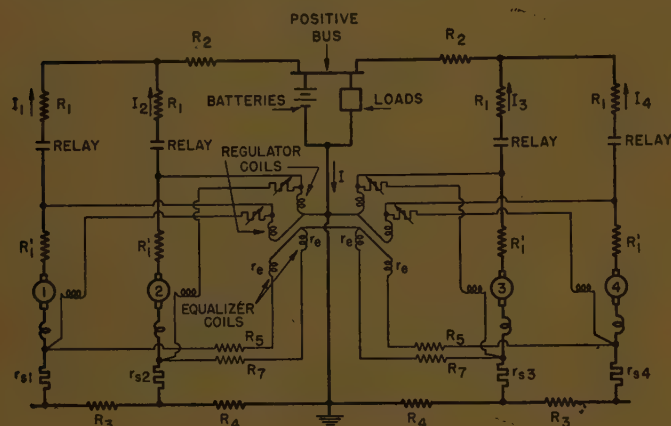


Figure 11. Connections of four-generator aircraft electric-supply system

field-circuit resistance causes decreases of approximately 7.5 amperes and 14 amperes in the peak outputs of compensated generators and uncompensated generators, respectively. A ten-degree-centigrade rise in field temperature will produce approximately a 0.1-ohm increase in field resistance. From the foregoing, it can be said that from the standpoint of increase in field-circuit resistance alone, the effect of temperature rise on an uncompensated machine is approximately twice that on a compensated machine. At heavy loads each ten-degree-centigrade rise in temperature will decrease the maximum output of an uncompensated machine approximately 14 amperes. For the compensated machine the decrease will be only 7.5 amperes.

Multigenerator Systems

(a). DESCRIPTION

Four generators are operated in parallel as shown in Figure 11. Each regulator is provided with an equalizer winding which is wound in a direction such as to compensate for the unbalanced load between generators. Equalizer potential is obtained by using the drop in resistors of equal value in the negative leads of the generators. Regulators are usually installed in the fuselage of the airplane

are negative-circuit resistances set up by the bonding of the negative leads to the structure of the airplane and the structure of the airplane itself; R_6 and R_7 are equalizer-lead resistances; r_e is the resistance of the equalizer coil; r_s is the resistance of the equalizer shunts; I_1 , I_2 , I_3 , and I_4 are the currents supplied by the generators; and I is the total load current.

If it is assumed that the identical voltage regulators have equal no-load settings, analysis of the aforementioned system indicates that load division is affected primarily by the shunt and ground resistances, r_s and R_3 respectively. If the various shunt resistances are equal, that is, if $r_{s1}=r_{s2}=r_{s3}=r_{s4}=r_s$, and if the voltage-regulator no-load settings are equal, the load division may be written approximately in terms of the following equations:

$$I_1 = I_4 \quad (1)$$

$$I_2 = I_3 \quad (2)$$

$$\frac{I_1}{I} \approx \frac{1}{2 \left(2 + \frac{R_3}{r_0} \right)} \approx \frac{I_4}{I} \quad (3)$$

From equation 3, it may be seen that if R_s and r_s are equal, machines 1 and 4 will each supply only one sixth of the total current instead of one fourth of the total which is desired. (Machines 2 and

3 will each supply one third of the total current.) It is apparent that a decrease in the grounding resistance R_3 is necessary to improve load division. It has been found that the unbalance in the negative leads, R_3 , is due to two things:

1. The resistance of the grounding structure itself (bolts, lugs, brackets, and so forth).
2. The fact that the lead resistances have not been equalized.

The airplane structure itself offers negligible resistance to the flow of current. If care is taken to make the negative leads of equal resistance and to ground the leads to a heavy portion of the airplane structure, R_3 becomes negligible ($R_3 \approx 0$) and the balance under load is materially improved. If perfect load division were required, it would be necessary to balance the positive-lead resistances, R_1 , the equalizer-lead resistances, and the regulator leads from the generator to the regulator coil. However, the effect on load division of unbalanced resistances in these leads is of second order. Their resistances, particularly those of the field leads, should be kept as low as possible in order to obtain maximum possible output from the generators.

2. *Unbalances Due to Voltage Regulators.* In addition to unbalance in load division due to the airplane circuits, considerable load unbalance can result from differences in voltage-regulator settings as small as ± 0.5 volt. For example, it is obvious that an undesirable current unbalance would exist if the regulators on the *outboard* generators were set at 28 volts, while the *inboard* regulators were set at 29 volts. This difference in voltage-regulator settings may result in load unbalances as high as ± 20 amperes (in systems employing an equalizer shunt voltage drop of 0.5 volt at 200 amperes) independent of unbalances due to unbalanced circuit resistances.

Variations from one regulator to another, as regards the ability of the regulator to hold voltage under all conditions of load, generator speed, and temperature will introduce additional unbalance in load division.

3. *Effect of Removing Generators From Service While the Corresponding Equalizer Coils Remain Connected.* It has been found by calculation and from test data that the effect of a "dead"* equalizer coil, or coils, upon *load division* is of secondary importance.

Dead equalizer coils, however, tend to reduce the system voltage. Both tests

* An equalizer coil which remains connected to the system after its generator has been removed from

and calculations indicate that, with the present voltage regulator using an equalizer shunt voltage drop of 0.5 volt at full load, the drop in system voltage, assuming that all equalizer coils remain connected and that the generators remaining in service are fully loaded is shown in Table I.

For systems which make use of a greater equalizer shunt voltage drop, the drop in system voltage due to dead equalizer coils will exceed the values indicated in Table I.

(c). VOLT-AMPERE CHARACTERISTIC

A typical curve of bus-voltage versus load current for a four-generator system is as shown in Figure 12. This system in-

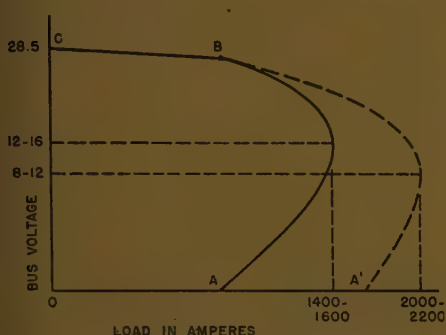


Figure 12. Volt-ampere characteristic of four-generator aircraft electric-supply system

Generators operating at 2,500 rpm

cludes voltage regulators and a battery. The portion of the curve *CB* has a slight droop with increasing load because of resistance between the bus and the points at which voltage is being regulated.

At point *B* the voltage regulators have reduced their variable resistance elements to the minimum ohmic values and are, therefore, essentially inoperative for the portion of the curve *BA*. Point *A* represents the value of short-circuit current contributed by the battery.

The effect of the battery, or batteries, is to produce a "stiffer" system, that is, to increase the maximum number of amperes available. This factor becomes important in the case of shock loads such as turret starting, and so forth. Shock loads should not be of such a resistance as to result in a collapse of system voltage. Curve *A'BC* is similar to

curve *ABC*, except that the system includes three batteries rather than one. A comparison of the two curves illustrates the additional "stiffness" obtained by adding batteries to the electric system.

For higher generator speeds, the maximum current available will exceed the values indicated in Figure 12 and will occur at somewhat lower voltages. The upper limits on maximum currents at high generator speeds will be governed by commutation, compensation, and saturation characteristics of the generators. It is quite possible that, with three batteries and generator speeds of 4,000 rpm, currents as high as 4,000 amperes may be obtained.

(d). TRANSIENT LOADING

One of the most severe transients experienced on the electric system of military airplanes is caused by the starting of a turret motor Amplidyne or motor generator set. Figure 13 shows the varia-

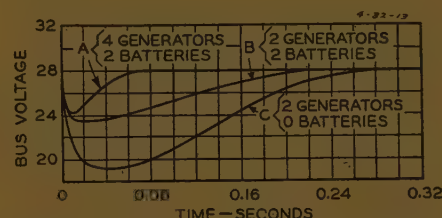


Figure 13. Bus voltage transient when motor Amplidyne set is started on an aircraft electric system

Generators operating at 3,000 rpm

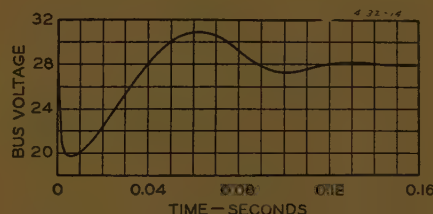


Figure 14. Bus voltage transient when landing gear is raised on four-generator aircraft electric system

Generators operating at 3,000 rpm. Three batteries on bus

tion in d-c bus voltage when a motor Amplidyne set is started on a four-engined airplane equipped with carbon-pile generator-voltage regulators. These transients were replotted from oscillograms taken during test flights.

The effect of the removal of generators and batteries from the supply system is clearly shown on the curves. A convenient basis upon which to compare different recovery characteristics for a constant loading condition is the area under the curves in volt-seconds. On

this basis a relatively small area would correspond to a quick recovery and a small initial disturbance. For Figure 13 the following comparisons may be made:

Case	System Conditions	Volt-Seconds
A.....	4 generators, 2 batteries.....	0.12
B.....	2 generators, 2 batteries.....	0.52
C.....	2 generators, 0 batteries.....	1.21

Figure 13 and the preceding tabulation show clearly the effect of the loss of generators and batteries on the system transient characteristics.

Another severe transient load is that of the retraction of electrically operated landing gear. Figure 14 shows the variation in bus voltage when the landing gear of a four-engined plane is retracted. Actually the gear requires 20 to 30 seconds to retract fully. Figure 14 shows the initial transient, which is followed by a comparatively steady-state load of about 300 amperes of 20 to 30 seconds duration.

A 500-ampere resistance load suddenly applied to the system will cause a bus-voltage variation similar to that shown in Figure 15. Figures 14 and 15 are replots of oscillograms taken during actual flight tests on an airplane with four generators and three batteries supplying the electrical power.

(e). SHORT-CIRCUIT CURRENTS

Both test and analytic studies of a typical multigenerator electric-power-supply system indicate, as shown in Table II, approximate values of maximum sustained* short-circuit current as a func-

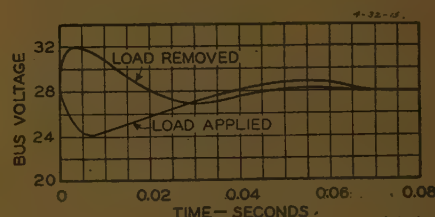


Figure 15. Bus voltage transient when 500-ampere resistance load is suddenly applied to a four-generator aircraft electric system

Generators operating at 3,000 rpm

tion of system generating capacity (assuming that there is no motor load on the system):

With four 200-ampere generators and three 24-volt batteries in service, the approximate maximum value of reverse current (sustained) through any re-

* "Sustained" short-circuit current is herein defined as that short-circuit current which can be maintained for a few seconds rather than a period of minutes.

Table II

Number of 200-Ampere Generators	Number of 24-Volt Batteries	Approximate Maximum Sustained Fault Current in Amperes
4.....	3.....	3,400
3.....	3.....	3,000
2.....	3.....	2,500
4.....	2.....	2,800
4.....	1.....	2,400

verse-current relay is 3,000 amperes. This condition can occur when the short circuit is located between a generator and its corresponding reverse-current relay.

In general, the magnitude of short circuit is dependent chiefly on the fault resistance and the number of generators and batteries in service. That is, for a given value of fault resistance and for a given number of generators and batteries in service, the short-circuit current has about the same value for a fault at any point in the supply system. The magnitude of short-circuit current also de-

For a fault on a wing junction box, the fault current as a function of fault resistance is shown in Figure 16. For faults at the various generators and nacelle junction boxes, the results are much the same as shown in Figure 16.

Test and calculated data indicate that only for extremely small values of fault resistance does the initial short-circuit current exceed the sustained value. This is shown in Figure 16. At low generator speeds, however, the initial value is more likely to exceed the sustained value than at high generator speeds. The initial short-circuit current decreases with fault resistance, as shown in Figure 16, and becomes practically equal to the sustained value for fault resistances in excess of 0.001 to 0.002 ohm. The initial value is also a function of system loading prior to the fault, increasing somewhat as the system load previous to the fault is increased. In general, it is expected that the fault resistances actually encountered in practice will be of the order of magnitude to result in short-circuit currents having about the same initial and sustained values. Oscillographic records obtained on a laboratory test setup tend to confirm this conclusion. For this reason, the preceding explanation has been confined to sustained short-circuit currents.

Figure 17 illustrates the typical short-circuit-current characteristics as obtained by means of an oscillograph. The values indicated on the figure were obtained with four 200-ampere generators and three 24-volt aircraft batteries in service and correspond to fault resistances of 0.006 ohm and 0.001 ohm.

It may be seen from Figure 17 that even when the initial short-circuit current exceeds the sustained value, the initial transient is very short. It is thus improbable that the operation of most protective devices would occur before the sustained value of current was attained.

(f). REVERSE-CURRENT PROTECTION OF GENERATOR AND BATTERY CIRCUITS

The short-circuit currents for faults in the generator and battery circuits may vary over a large range of values depending on the fault resistance and operating conditions prior to the fault.

Also, for a given fault, the short-circuit currents contributed by the various generators are nearly equal. The difficulty, then, in obtaining adequate short-circuit protection with devices utilizing current magnitude only is obvious.

It is apparent, however, that for a given fault in the generator or battery circuits, the direction of current flow in the faulted circuit element is opposite to the normal direction of flow. Thus reverse current may be used to trip reverse-current circuit breaker or switch to clear the fault.

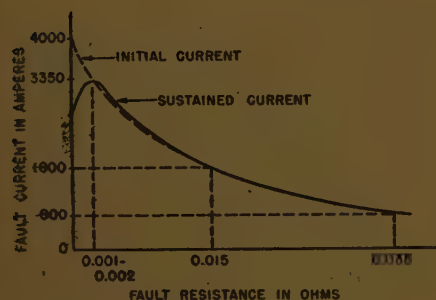


Figure 16. Fault currents on a four-generator aircraft electric system as a function of fault resistance

Three batteries in service

pends to some extent upon the speed of the generators. Table II was calculated on the basis of a generator speed of 3,200 rpm, assuming characteristics similar to those of a generator rated 5.7 kw, 28.5 volts, 200 amperes, 2,500/4,500 rpm, with commutating and compensating windings. Test results on this type of generator indicate that the short-time volt-ampere characteristic at 3,200 rpm is representative of the maximum sustained short-circuit current which the generators can deliver for a few seconds, even though the generator speed is higher than 3,200 rpm. Since both test and calculated results indicate that uncompensated generators produce appreciably less current at the low voltages encountered during short circuits, it is expected that the numerical results presented in Table II represent the maximum values of short-circuit current which may be expected.

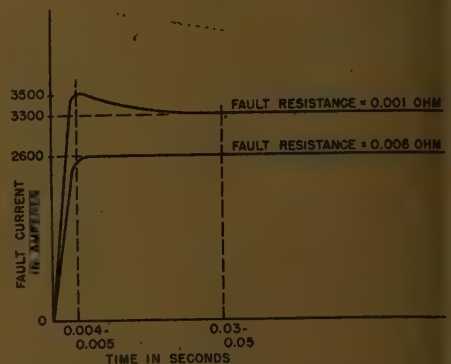


Figure 17. Short-circuit characteristic of a four-generator aircraft electric system

Three batteries in service

It is believed that a reverse-current circuit breaker is fundamental to the reliable protection of generator and battery circuits.

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Heating of Nonmagnetic Electric Conductors by Magnetic Induction—Longitudinal Flux

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HEAT can be generated in a piece of metal or other conducting material by wrapping a coil around the piece, such as the cylinder shown in Figure 1a, and causing a current of suitable magnitude and frequency to flow into the coil. This is called "induction heating." The great advantage of this type of heating is that the heating can be accomplished without contacting the piece to be heated. This allows the heating to take place while the piece is moving or enclosed in a protective atmosphere. Also, the heat usually can be concentrated just where it is needed, and a piece usually can be heated faster by induction than by any other method. The desirable frequency to use for induction heating depends on the size and the electrical properties of the piece to be heated and may vary from 25 or 60 cycles per second for heating joints in iron pipes to a few million cycles per second for heating very small nonmagnetic pieces for soldering. Frequencies up to 10,000 cycles per second are obtained usually from rotating machines; for higher frequencies one must resort to spark or vacuum-tube oscillators.

Induction heating finds a multitude of uses in industrial processes, such as surface hardening or heat treating, heating slugs in a continuous process for forging, heating joints for brazing, continuous heating of moving magnetic strip or wire, and the heating of small nonmagnetic terminals for soft soldering. A very successful recent application of induction heating is the use of radio-frequency power to brighten electrolytic tin plate. In this process the tin surface on the strip is melted continuously with the strip moving at 1,000 feet per minute and with an input of about 1,200 kw of 200-kilocycle power to the heating coil.

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Some of the applications require the heating of magnetic material, such as iron and steel, which usually are easy to heat. Others require the heating of nonmagnetic materials, such as brass or copper, which can be heated less readily, especially when the piece to be heated is small and has a low electrical resistivity.

Since it is impractical to cover the whole field of induction heating in one

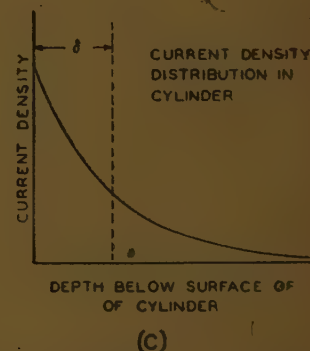
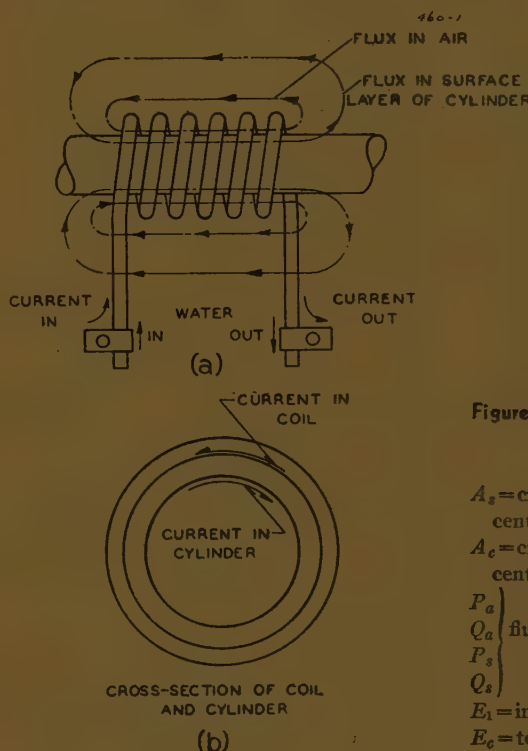


Figure 1. Induction heating of a nonmagnetic cylinder

paper, this paper will be limited to the heating of nonmagnetic materials.

Almost any problem in induction heating can be resolved into the problem of heating a cylinder, a flat slab or strip, or a surface by a current-carrying conductor near the surface. The following discussion of these three cases, therefore, should enable one to calculate any problem where the material to be heated is nonmagnetic.

List of Symbols

Symbols will be defined throughout the paper the first time they are used, but

for convenient reference all symbols are listed here:

f =frequency (cycles per second)
 a =radius of a cylinder (centimeters)
 d =diameter of a cylinder (centimeters)
 ρ =electrical resistivity (ohm-centimeters)
 $G_a(K_a a)$ =a function of $(K_a a)$ (Figure 2)
 $G_s(K_s t)$ =a function of $(K_s t)$ (Figure 9)
 t =thickness of slab (centimeters)
 t_w =thickness of cylinder wall (centimeters)
 H =peak magnetizing force at surface of piece to be heated (oersteds)
 T_c =turns in heating coil
 I_c =current in coil (rms amperes)
 l_c =length of coil (centimeters)

$$K_a = \sqrt{\frac{8\pi^2 f 10^{-9}}{\rho}}$$

$$K_s = \sqrt{\frac{4\pi^2 f 10^{-9}}{\rho}}$$

ϕ_a =flux inside cylinder

ϕ_s =flux inside slab

A_a =cross-sectional area of cylinder (square centimeter)

A_s =cross-sectional area of slab (square centimeters)

A_c =cross-sectional area of coil (square centimeter)

P_a
 Q_a flux coefficients for cylinders and slabs
 P_s (see Figures 3 and 10)
 Q_s

E_i =internal voltage of coil (rms volts)

E_c =terminal voltage of coil (rms volts)

(Power factor)₁=cos θ_1 =internal power factor of coil

cos θ_c =terminal power factor of coil

W_w =total watts into piece to be heated

R =resistance of coil at the frequency used

δ =effective depth of current penetration (centimeters)

f_p =see equation 16

f_s =see equation 17

l_a =axial length of cylinder (centimeters)

l_s =length of slab (centimeters)

x =distance from center line of conductor (centimeters)

I =conductor current (rms amperes)

h_1 =distance from center of conductor to surface of plate

h =equivalent distance defined by equation 27

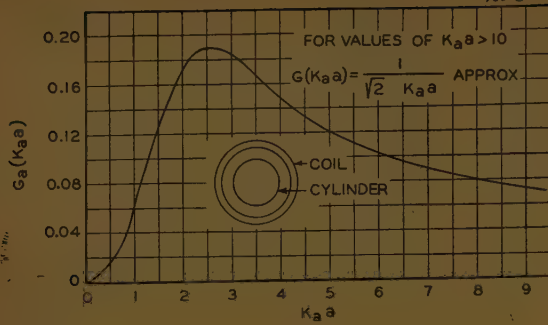


Figure 2 (left). Non-magnetic cylinder $G_a(K_a a)$ as a function of $(K_a a)$

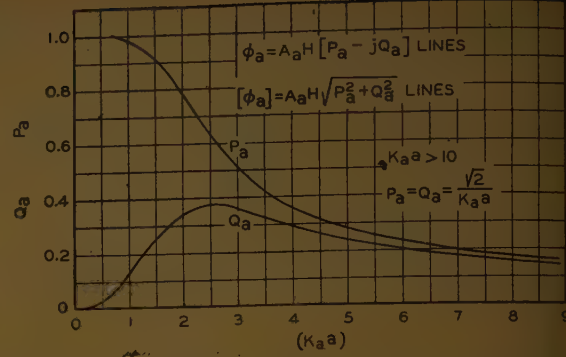


Figure 3 (right). Flux inside nonmagnetic cylinder

K_r = empirical resistance coefficient
 R_0 = d-c resistance of solid copper conductor (equation 23)
 p_c = inside perimeter of coil (centimeters)
 p_w = outside perimeter of work (centimeters)
 l_w = axial length of work (centimeters)
 ρ_c = resistivity of copper (ohm-centimeters)
 ρ_w = resistivity of work (ohm-centimeters)
 $W_c = I_c^2 R$ = copper loss in coil (watts)
 W = watts per square centimeter or per cubic centimeter

General Consideration of the Induction-Heating Process

When current is caused to flow in the coil (heating coil) surrounding the work-piece, such as the cylinder of Figure 1a, a countercurrent is induced in the work-piece, as illustrated in Figure 1b. The current density is highest at the surface and drops off exponentially inside as shown in Figure 1c. The heating in the piece due to this varying current density is the same as would be caused by the same total integrated current distributed uniformly in a surface layer of thickness δ (Figure 1c). The depth δ is called the effective depth of penetration of current, and, in special cases, it may be used conveniently to calculate induction-heating problems. This paper, however, is concerned with more general methods of calculation, and the depth of penetration concept will be used only in treating the problem of thin-walled cylinders.

Heating of Nonmagnetic Solid Cylinders

The power generated in a nonmagnetic cylinder can be calculated from the equation¹

$$W = 1/2 H^2 f G_a(K_a a) 10^{-7} \quad \text{watts per cubic centimeter} \quad (1)$$

where

$$K_a a = a \sqrt{\frac{8\pi^2 f 10^{-9}}{\rho}}$$

f = frequency (cycles per second)
 a = radius of cylinder (centimeters)
 ρ = electrical resistivity of cylinder (ohm-centimeters)

$G_a(K_a a)$ = a function of $(K_a a)$ involving Bessel's functions and plotted for convenience in Figure 2

H = peak value of magnetizing force at the surface of the cylinder (oersteds)

If the magnetizing coil has closely spaced turns and a length equal to at least 20 times the spacing between the cylinder and the inside diameter of the coil, the end effect of the coil is negligible, and one may calculate H from the equation

$$H = \frac{0.4\pi T_c I_c \sqrt{2}}{l_c} \quad \text{oersteds} \quad (2)$$

T_c = turns in coil

I_c = current in coil (rms amperes)

l_c = axial length of coil (centimeters)

If a relatively shorter coil is used, the actual H obtained will be less than that indicated by equation 2. This effect, however, will not be considered in this paper.

The magnetic flux in the air space between the cylinder and the inside diameter of the coil will be $(A_c - A_a)H$ where A_c is the cross-sectional area of the coil (square centimeters) corresponding to its inside diameter, and A_a is the cross-sectional area of the cylinder (square centimeters). Some flux also penetrates the cylinder, and the magnitude of this flux may be calculated from

$$\phi_a = A_a H (P_a - jQ_a) \quad (3)$$

where P_a and Q_a are quantities proportional to the two components of this flux and are plotted for convenience in Figure 3. The total flux linking the coil is then the vector sum of the flux in the air $(A_c - A_a)H$ and the flux in the cylinder $A_a H (P_a - jQ_a)$. If these two are added, one obtains for the total flux

$$\phi_0 = A_c H \left[\left(\frac{A_c}{A_a} - 1 + P_a \right) - jQ_a \right] \quad \text{lines} \quad (4)$$

or in actual magnitude

$$|\phi_0| = A_c H \sqrt{\left(\frac{A_c}{A_a} - 1 + P_a \right)^2 + Q_a^2} \quad \text{lines} \quad (5)$$

The voltage induced by this flux in the turns of the coil will be

$$E_1 = \sqrt{2} \pi f T_c |\phi_0| 10^{-8} \quad \text{volts (rms)} \quad (6)$$

From equations 1, 2, 5, and 6 one may calculate power into the work, coil current, and coil voltage for a variety of conditions. If these quantities are known, one may calculate the corresponding values of what will be termed "internal power factor." The internal power factor will be defined by the equation

$$(\text{Power factor})_1 = \cos \Theta_1 = \frac{W_w}{E_1 I_c} \quad (7)$$

where W_w is the total power in watts put into the work. It is found that the internal power factor is represented by the equation

$$\cos \Theta_1 = \frac{2G_a(K_a a)}{\sqrt{\left(P_a + \frac{A_c}{A_a} - 1 \right)^2 + Q_a^2}} \quad (8)$$

Curves of internal power factor for various values of A_c/A_a are represented by the curves of Figures 4 and 5. The parameter $K_a a$ is used in equation 8 and in plotting the curves of Figures 4 and 5, so as to make them perfectly general and applicable to any frequency and any cylinder. One may calculate values of $\cos \Theta_1$ for $(K_a a)$ values greater than 10 by using the relation

$$K_a a > 10 \quad P_a = Q_a = \frac{\sqrt{2}}{K_a a} \quad (9)$$

$$G_a(K_a a) = \frac{1}{\sqrt{2} K_a a}$$

The voltage E_1 does not include the voltage drop due to the resistance of the heating coil nor to flux which actually passes through the turns (through the copper) of the coil. The coil should always be designed, so that the depth of penetration of flux and current is less than the thickness of the copper from which the coil is wound, and for this condition and for a close-wound coil the voltage drop due to flux inside the copper will be approximately equal to the resistance drop of the coil. The volt-amperes consumed in the copper of the coil on this assumption will be $I_c^2 R(1+j)$ or will have the absolute value $\sqrt{2} I_c^2 R$ where R is the resistance of the coil at the fre-

frequency used. The total volt-amperes at the terminals of the coil may be obtained by adding the volt-amperes in the copper of the coil to the volt-amperes $E_1 I_c$, as shown in Figure 6a. This diagram is drawn for the case where the value of volt-amperes in the copper of the coil $\sqrt{2} R I_c^2$ is small compared with $E_1 I_c$. The actual volt-amperes input to the coil is, in this case, only slightly greater than the internal volt-amperes $E_1 I_c$, and the power factor at the coil terminals $\cos \Theta_c$ differs only slightly from the internal power-factor $\cos \Theta_1$.

One may calculate the total volt-amperes in the coil from the internal volt-amperes $E_1 I_c$ and the relation

$$E_1 I_c = \sqrt{(E_1 I_c \cos \Theta_1 + I_c^2 R)^2 + (E_1 I_c \sin \Theta_1 + I_c^2 R)^2}$$

volt-amperes (10)

where

$$\cos \Theta_1 = \frac{W_w}{E_1 I_c}$$

Figure 6b represents approximately the conditions which would be obtained in heating a copper cylinder with the heating coil wound closely around the copper cylinder and with the frequency high enough to make the internal power factor equal to 0.707. This is not a condition likely to be obtained in practice but is included to show that, in an extreme case, the volt-amperes in the copper of the coil may be equal to half the total volt-amperes supplied at the terminals of the coil.

The actual power factor at the terminals of the coil is

$$\cos \Theta_c = \frac{W_w + I_c^2 R}{E_1 I_c} \quad (11)$$

The curves of Figures 4 and 5 are valid only when the cylinder to be heated is equal in length or longer than the heating coil. The internal power factor for the case where the coil is slightly longer than

the cylinder, as often will be the case, may be estimated by reducing the values given by these curves in the ratio l_a/l_c where l_a is the length of the cylinder in centimeters.

It is, in general, desirable to operate at a frequency equal to or greater than that which will give the maximum internal power factor. From the curves of Figures 4 and 5 this corresponds to a value of $K_a a \geq 3$. Solution for the corresponding frequency indicates that the frequency to use is

$$f \geq \frac{114 \rho 10^6}{a^2} \text{ cycles per second} \quad (12)$$

In some cases, where a very large cylinder of low resistivity is to be heated, this equation may indicate a minimum frequency which is absurdly low from the standpoint of the generator. In such cases, a higher frequency should be used. Also, since a low frequency requires a thick conductor in the heating coil, the mechanical considerations of coil design may force one to use a higher frequency than that which would give a maximum internal power factor. There will be other cases where one wishes to heat only a very thin layer on the surface of the cylinder. In this instance, the frequency should be chosen high enough to make the effective depth of penetration of current defined by the equation

$$\delta = 5,030 \sqrt{\frac{\rho}{f}} \text{ centimeters} \quad (13)$$

equal to or less than the depth to which heating is desired.

Heating of Hollow Nonmagnetic Cylinders

If one desires to heat a hollow nonmagnetic cylinder having a wall thickness equal to or greater than about one-tenth its diameter, the frequency should be chosen to make δ (equation 13) equal to

or less than the wall thickness and use the method of calculation for solid cylinders. The only precaution necessary is to remember that equation 1 gives the average watts per cubic centimeter in a solid cylinder, and, since the total power input to the hollow and solid cylinders will be equal when δ is equal to or less than the wall thickness (t) of the hollow cylinder, the watts per cubic centimeter in the hollow cylinder will be greater than that indicated by equation 1 in the ratio of the cross-sectional area of the solid cylinder to that of the hollow cylinder.

Heating of Thin-Walled Hollow Cylinders

When the wall thickness of a cylinder becomes less than about one-tenth the diameter, one can obtain satisfactory heating with a frequency less than that which makes δ equal to the wall thickness. When the depth of penetration is several times the wall thickness, the cylinder may be considered as a short-circuit secondary of an air-cored transformer with uniform current density throughout the thickness of the wall. For this condition it can be shown that the power input to the cylinder is

$$W = \frac{1.23 f^2 d^2 t_w \rho H^2 10^{-16}}{\rho^2 + 3.87 t_w^2 f^2 d^2 10^{-16}} \quad (14)$$

watts per square centimeter

d = outside diameter of cylinder (centimeters)

This equation is applied to a thin-walled brass cylinder with the results plotted in Figure 7 (curve B). It is seen that the power input increases rapidly at first, as the frequency is increased, and then becomes constant. The vertical dotted lines indicate the frequency f_p where the input has reached 90 per cent of the value it has in the flat part of the curve and f_s , the frequency at which the depth of penetration δ becomes equal to the wall thickness. Equation 14, of course, is no longer valid when δ approaches or gets less than the wall thickness, but in this region one may use equation 1 with the approximation $G_a(K_a a) =$

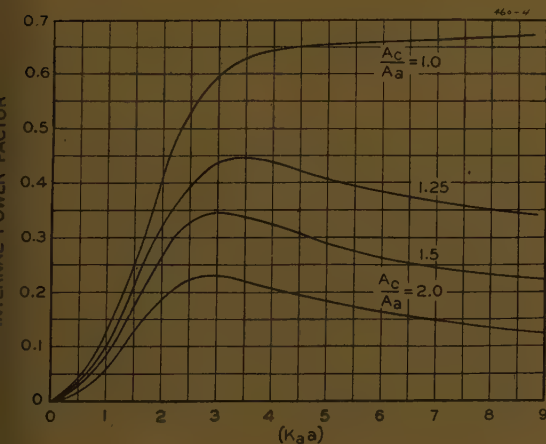
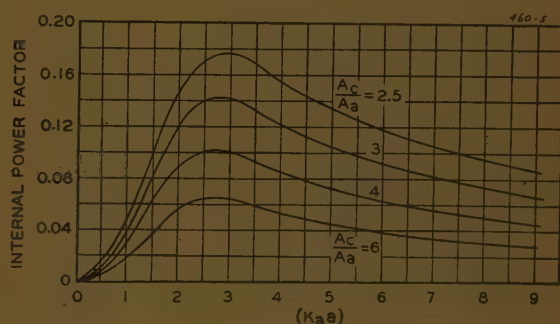


Figure 4. Internal power factor for nonmagnetic cylinder
Cylinder longer than coil

Figure 5 (right). Internal power factor for nonmagnetic cylinder

Cylinder longer than coil



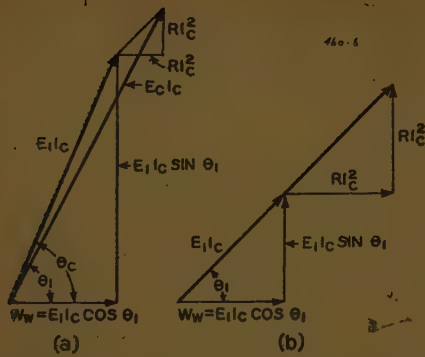


Figure 6. Vector diagrams of volt-amperes in coil

- (a). Heating high-resistance material
(b). Heating low-resistance material

$1/\sqrt{2}K_a a$. When rewritten, this equation becomes

$$W = 0.63 \times 10^{-4} H^2 \sqrt{\rho_f} \quad \text{watts per square centimeter} \quad (15)$$

Calculation of the hollow brass cylinder with this equation gives curve A (Figure 7). This equation is not valid when δ is greater than the wall thickness of the cylinder but agrees well with equation 14 when $\delta = t_w$. The two curves probably can be joined with the dotted curve shown. It seems, therefore, that one can, with little error, calculate with equation 14 below f_δ and with equation 15 above f_δ . The two frequencies f_p and f_δ will come closer together when the ratio of diameter so wall thickness is decreased (Figure 8). These frequencies may be expressed as

$$f_\delta = \frac{153 \rho 10^6}{t_w d} \quad (16)$$

and

$$f_\delta = \frac{25.6 \rho 10^6}{t_w^2} \quad (17)$$

The ratio of these frequencies is

$$\frac{f_\delta}{f_p} = 0.167 \frac{d}{t_w}$$

This shows that the two frequencies coincide approximately when $d/t_w = 6$ and are farther apart the greater the ratio d/t_w . If satisfactory power input can be obtained at the frequency (f_δ), one may as well operate at the lower frequency (f_p) or at some intermediate frequency. Only in cases of extreme power input should it be necessary to go to a frequency greater than (f_δ).

Heating of Nonmagnetic Slabs or Strip

A flat nonmagnetic slab, thin in comparison with its width (see cross-section view Figure 9), can be heated by induction, and the power input is given by²

$$W = 1/2 H^2 G_s(K_s t) 10^{-7} \quad \text{watts per cubic centimeter} \quad (18)$$

where

$$K_s t = \sqrt{\frac{4 \pi^2 f 10^{-9}}{\rho}}$$

t = thickness of slab (centimeters)

$G_s(K_s t)$ = a function of $K_s t$ given in Figure 9

As in the case of the cylinder, the magnetizing force may be calculated from equation 2, and the internal voltage E_1 may

be calculated from equation 6. The total flux inside the coil for this case will be

$$\phi_0 = A_s H \left[\left(\frac{A_c}{A_s} - 1 + P_s \right)^2 - j Q_s^2 \right] \text{ lines} \quad (19)$$

or in actual magnitude

$$[\phi_0] = A_s H \sqrt{\left(\frac{A_c}{A_s} - 1 + P_s \right)^2 + Q_s^2} \text{ lines} \quad (20)$$

where

A_s = cross-sectional area of slab (square centimeters)

A_c = inner cross-sectional area of coil (square centimeters)

P_s and Q_s are given by the curves of Figure 10.

The internal power factor will be

$$\begin{aligned} (\text{Power factor})_1 &= \cos \theta_1 \\ &= \frac{2 G_s(K_s t)}{\sqrt{\left(P_s + \frac{A_c}{A_s} - 1 \right)^2 + Q_s^2}} \end{aligned} \quad (21)$$

Values of internal power factor for various values of the ratio A_c/A_s are plotted in Figures 11 and 12. If values taken from these curves are used, the total volt-amperes in the coil and the true power factor at the terminals of the coil may be calculated from equations 10 and 11, respectively.

As in the case of the cylinder, the curves of Figures 11 and 12 are good only if the slab is equal in length or longer than the coil. If the length of the slab is only a little less than the length of the coil, the internal power factor may be obtained by

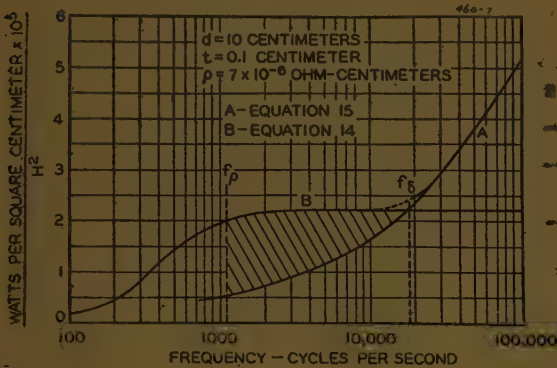


Figure 7 (left). Power input to hollow brass cylinder

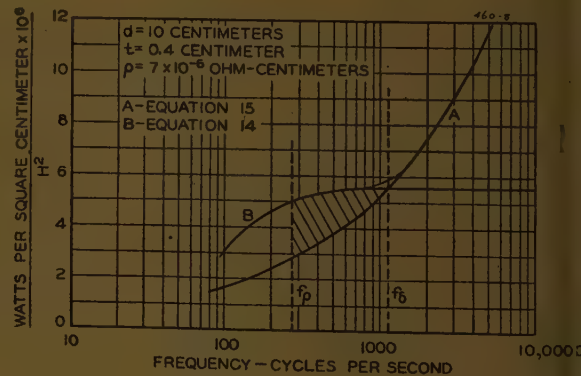


Figure 8 (right). Power input to hollow brass cylinder

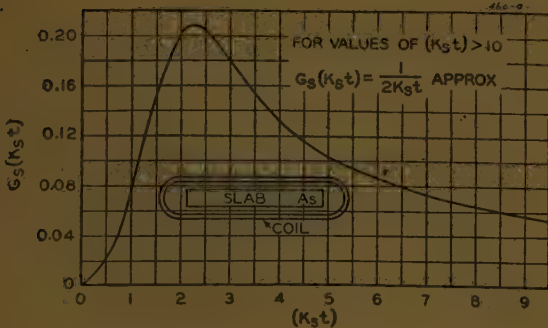


Figure 9 (left). Non-magnetic slab or strip $G_s(K_s t)$ as a function of ($K_s t$)

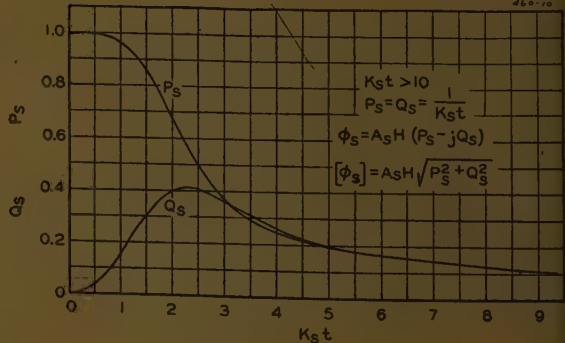


Figure 10 (right). Flux inside non-magnetic slab or strip

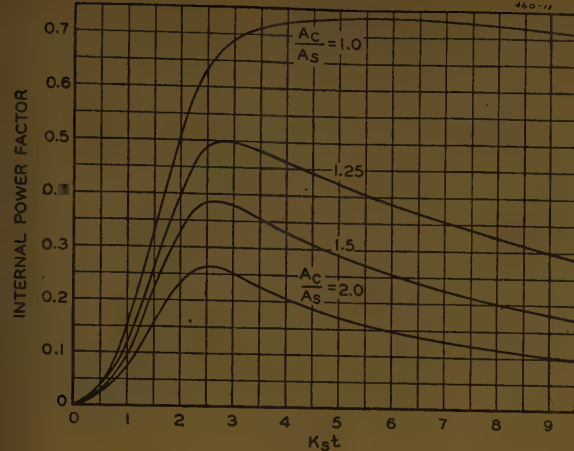


Figure 11 (left). Internal power factor, nonmagnetic slab or strip

Slab or strip longer than coil

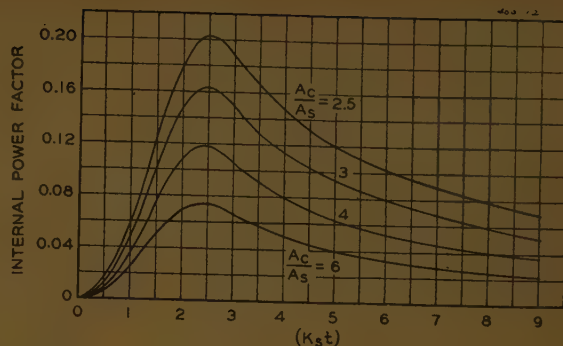


Figure 12 (right). Internal power factor, nonmagnetic slab or strip

Slab or strip longer than coil

reducing the value given by the curves in the ratio l_s/l_c , where l_s is the length of the slab in centimeters.

Since the internal power-factor curves of Figures 11 and 12 peak around 2.5 in the practical range of the ratio A_c/A_s , it can be agreed that the frequency to be used in heating a nonmagnetic slab is determined by the relation $K_s f \geq 2.5$ or

$$f \geq \frac{158 \rho 10^6}{l^2} \text{ cycles per second} \quad (22)$$

Heating Cylinders and Slabs of Small Diameter or Thickness

The analysis given previously may be applied to small nonmagnetic wires and thin nonmagnetic sheet, but, because it is difficult to construct a coil to conform closely to the surface of the work in these cases, it is found that the power factor of the heating coil and the efficiency of the process are extremely low. Small-diameter iron wire and thin iron sheet, on the contrary, may be heated quite efficiently, because the magnetic permeability acts to increase the skin effect greatly.

Approximate Calculation of I^2R Loss in Coil—Coil Efficiency

Some work has been done to develop formulas to predict the high-frequency resistance of coils of simple shapes, but these equations are generally tedious to use and are useless for irregularly shaped coils. The writer has found it convenient in the case of coils wound from hollow copper tubing to calculate the high-frequency resistance of the length of tubing used in a coil, as if it were a straight isolated conductor, and then multiply this value of resistance by a factor K_r greater than unity to take into account the fact that the tubing is wound into a coil.

In accordance with the aforementioned material, one may write for the resistance

at the frequency (f) of a coil wound from hollow copper tubing¹

$$R = K_r R_0 (0.038 d \sqrt{f} + 0.25 \text{ ohms}) \quad (23)$$

K_r = empirica¹ resistance factor

d = outside diameter of tubing (centimeters)

R_0 = d-c resistance of a solid round copper conductor having the same outside diameter and same length as the tubing used in the coil

f = frequency in cycles per second

Tests indicate that the high-frequency resistance of single-layer coils of circular cross-section wound from one-fourth-inch outside diameter to one-half-inch outside diameter copper tubing with diameters from two to four inches and lengths equal to or greater than their diameters may be calculated fairly accurately from equation 23 by using values of K_r given in Figure 15. Some tests made on coils of rectangular or oblong cross section (width more than five times the thickness) showed the resistance of this type of coil to be less frequency sensitive than the coils of circular cross section. The high-frequency resistance of this type of coil may be calculated approximately from equation 23, using the value $K_r = 2.5$.

It must be noted that, for equation 23 to be valid and also to obtain an efficient coil design, the wall thickness of the copper tubing used should be greater than the depth of current penetration, equation 13, at the frequency used. Above ten kilocycles, standard annealed copper tubing with an outside diameter of from one-fourth to one-half inch is satisfactory.

Another method of approximating the copper loss in the coil is to consider the fact that, when the frequency is high enough for satisfactory heating $K_s a \geq 3$ for cylinders and $K_s t \geq 2.5$ for flat plates, the current in the work and the ampere turns in the coil per centimeter length are approximately equal. If the coil were close wound of copper strap or a single cylindrical turn of copper, the ratio of loss

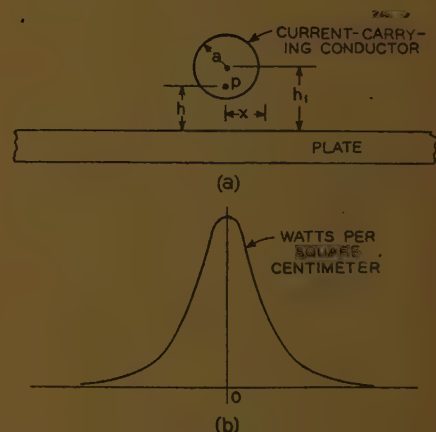


Figure 13. Heating surface of plate by proximity effect

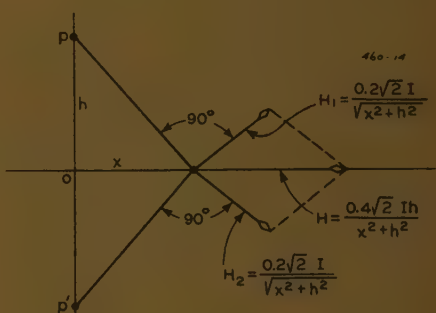


Figure 14. Magnetizing force H from two line conductors

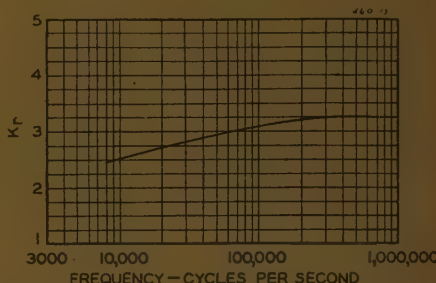


Figure 15. K_r versus frequency for use with equation 23

in the coil to power in the work (non-magnetic) should be approximately

$$\frac{W_c}{W_w} = \frac{p_c l_c}{p_w l_w} \sqrt{\frac{\rho_c}{\rho_w}} \quad (24)$$

p_c = inside perimeter of coil (centimeters)
 p_w = outside perimeter of work (centimeters)
 l_c = axial length of coil (centimeters)

l_w = axial heated length of work inside coil (centimeters)
 ρ_c = resistivity of copper (ohm-centimeters)
 ρ_w = resistivity of work (ohm-centimeters)

For the usual close-wound coil of copper tubing the ratio is more nearly

$$\frac{W_c}{W_w} = 1.3 \frac{\rho_c l_c}{\rho_w l_w} \sqrt{\frac{\rho_c}{\rho_w}} \quad (25)$$

The coil efficiency can be expressed as

$$\text{Coil efficiency} = \frac{1}{1 + \frac{W_c}{W_w}} \quad (26)$$

Equation 25 is fairly accurate if the depth of penetration (equation 13) is less than one-fourth the diameter of a cylinder or one-third the thickness of a slab and is quite useful with equation 26 to estimate the efficiency to be expected in a given heating job.

Equation 26, of course, will give the coil efficiency accurately if W_c and W_w are determined accurately.

Heating by Proximity Effect— Flat Nonmagnetic Plate

If a conductor carrying alternating current is arranged parallel with and close to the surface of a metal plate, as shown in Figure 13a, the magnetic field from this conductor will cause countercurrents to flow in the surface of the plate next to the conductor and to be concentrated approximately under the conductor. If the depth of penetration of current, equation 13, into the plate and into the conductor is small compared with the thickness of the plate and the distance between the conductor and the plate, the problem becomes very similar to the classical electrostatic problem of a charged cylinder near a metal plate.^{3,4} The magnetizing force at the surface of the plate is the same as would be caused by two line conductors carrying current in opposite directions, one at (p) height (h) above the surface of the plate and one at (p') distance (h) below the surface. The value of (h) is

determined from the height of the center of the conductor (h_1 centimeters) above the surface and the radius of the conductor (a centimeters) and the relation

$$h = \sqrt{h_1^2 - a^2} \text{ centimeters} \quad (27)$$

Figure 14 shows how the magnetizing forces of these two conductors add to give a resulting magnetizing force at and parallel to the surface of the plate at a point distance (x) from the origin. The value of this magnetizing force (peak) is

$$H = 0.4 \sqrt{2I} \frac{h}{x^2 + h^2} \text{ oersteds} \quad (28)$$

I = conductor current (rms amperes)

The heating in a surface for a given value of H parallel to the surface may be calculated from equation 15. If the value of H from equation 28 is substituted in equation 15, the density of heating at the surface of the plate is

$$W = 0.202 \times 10^{-4} I^2 \sqrt{\rho_f} \left(\frac{h}{x^2 + h^2} \right)^2 \text{ watts per square centimeter} \quad (29)$$

The curve of Figure 13b shows the power input to the surface calculated from equation 29 for the size of conductor and spacing shown in Figure 13a.

By integrating equation 29 from $x=0$ to infinity in both directions, it is found that the total power input to the plate by a conductor (l) centimeters long is

$$W = 0.316 \times 10^{-4} \frac{l^2 \sqrt{\rho_f}}{h} \text{ watts} \quad (30)$$

Equations 29 and 30 may be applied also to a single-turn circular coil around a cylinder, provided that the turn conforms closely to the surface of the cylinder. In this case, the value of (l) to use in equation 30 is the circumference of the cylinder. These equations break down in any case when (h) approaches zero because of the approximate assumptions on which they are based. They cannot be applied accurately if $h < 10\delta$ where δ is calculated for the workpiece from equation 13.

Conclusions

It will be found by an application of the methods described in this paper, that the majority of heating jobs on nonmagnetic workpieces having a minimum dimension of one-half inch or more can be accomplished satisfactorily with frequencies less than 10,000 cycles per second (rotating machine frequencies). Smaller sections may be heated with higher frequencies from vacuum-tube or spark-gap oscillators. Since it is difficult to obtain close coupling with small nonmagnetic pieces, such heating processes usually will be inefficient, although they may be feasible economically.

Hollow cylinders with thin walls often may be heated with frequencies much lower than the frequency required to heat a flat sheet equal in thickness to the wall thickness of the cylinder, as the cylinder acts as a short-circuited secondary winding.

The concept and method of proximity heating is very useful in applying induction heating locally to heat the workpiece. One should remember that, when the frequency is high enough, the currents in the inducing coil or conductor cause image currents to flow in and heat the workpiece.

When it is desired to heat a piece throughout, the minimum frequency indicated by equations 12 and 22 should generally be used; however, if a superficial heating of the surface is desired, a higher frequency should be used. In the latter case, the power input also must be high enough to establish the high temperature gradient necessary at the surface.

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Basic Considerations in Selection of Electric Systems for Large Aircraft

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Synopsis: This paper presents some of the considerations involved in selecting electric systems for large aircraft. Such systems are undergoing intensive development now; consequently it is not possible to give complete answers to all problems which arise. Also, certain parts of the electric systems are subject to military classification and cannot be discussed. Nevertheless it is felt that many engineers, particularly those engaged in the design of such systems, will welcome a brief review of the basic factors involved.

Industrial and central-station experience provide a valuable background for study of aircraft systems. However, too close an adherence to previous practice should not be maintained, since aircraft systems differ in many ways from those of land equipment. The need for minimum weight demands that only those features be included which fundamental considerations show to be necessary or which at least provide benefits that justify the weight involved.

ELECTRIC systems on aircraft have been undergoing continuous evolution since the airplane was invented. Early planes started with a six-volt d-c system patterned after the automobile. Increasing power requirements led, first, to the adoption of 12-volt systems and, later, to the 27-volt* d-c systems which are now in common use. A few airplanes have been operated with 120-volt d-c systems, and some with a-c systems having various frequencies ranging from 60 to 2,400 cycles per second.

The 27-volt d-c electric system for aircraft has done an excellent job to date. It is simple, light, easy to control, reliable, and the electric-shock hazard to personnel is negligible. Therefore, it is proper to ask, "Why not use this system for all planes, especially since wartime conditions already are straining our engineering and production facilities se-

verely?" The answer to this question lies in the fact that while the 27-volt system has proved satisfactory on the larger airplanes such as the B17 Flying Fortresses and the B24 Liberators, which are now performing in an excellent manner on our fighting fronts, there are new designs on the drafting boards to meet new military requirements. The size, performance, and electric load requirements of these proposed new planes are such that the 27-volt d-c system is no longer adequate or efficient from the standpoint of weight, and consideration must be given to new types of systems for these larger planes.

Since airplanes are designed for many different functions, it is not likely that a single type of system will be the best for every case, even among large planes. Thus, military-plane requirements differ from those of commercial planes. Small plane requirements differ from those of large planes. Altitude, range, nature of mission, and many other factors which are discussed in this paper, affect the choice of an electric system. It is believed that a review of the principal considerations involved will be of value in selecting a system for any given case.

Although the power system is always tailored to the airplane, there are some variables, such as operating voltage and frequency, which can be standardized at certain levels and thus provide the industry with the benefits of standardization. The United States Army Air Forces are contributing to electrical progress in this respect by their standardizing and co-ordinating work. The selection of 400 cycles for a-c systems for certain large military planes is a recent example.¹ A considerable part of this paper deals with problems encountered in such systems.

Purpose and Requirements of Electric System

The purpose of an electric-power system on an airplane is to generate and to distribute electric power to the various pieces of utilization equipment which are required on the airplane. The best system for any particular application is

the one which combines most effectively the following features:

1. Maximum reliability under all conditions encountered in operation
 - (a). Reliability of equipment such as motors and generators.
 - (b). Service continuity should be maintained automatically even during faults or emergency conditions, insofar as possible.
 - (c). Minimize hazard to operating personnel, airplane, and equipment.
2. Minimum weight
 - (a). Minimum installed weight.
 - (b). Maximum efficiency (fuel economy).
 - (c). Minimum additional aerodynamic drag for cooling requirements (fuel economy).
3. Minimum space requirements.
4. Simplicity
 - (a). Ease of operation.
 - (b). Minimum training time for operating and maintenance crew.
 - (c). Ease of maintenance in field.
 - (d). Rapid and accurate checking in field.
 - (e). Minimize spare-part requirements.
 - (f). Ease of installation
- (1). Initially.
 - (2). Replacement parts.
5. System should not interfere with the performance of the airplane or its equipment in any way, or at least as little as possible.
6. Satisfactory life of all component parts
 - (a). Minimum frequency of replacement.
 - (b). Minimum frequency of overhaul.
 - (c). Minimum frequency of maintenance.
7. Least cost in man-hours and dollars.
8. Utilize existing designs of aircraft accessory equipment as far as is practical.

The desirability of these features is self-evident and, therefore, need not be discussed in detail. However, it might be well to point out that certain factors are interrelated. For example, fuel consumption can be translated in terms of weight for a given-length flight. Ease of operation and maintenance are associated with service reliability et cetera. In diverse applications the various factors have different degrees of importance, and it is necessary to compromise on a system which provides the best over-all characteristics for the particular application under consideration.

The evaluation of weight and efficiency of aircraft accessory equipment is particularly important in long-range aircraft, since fuel must be provided not only to operate it but also to carry the fixed weight of the equipment plus any additional structural-weight requirements introduced by it and the necessary added fuel. Any increase in fixed weight tends

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* Sometimes referred to as 24-volt or 30-volt systems. Equipment for such systems is usually designed as follows: generators, 30 volts; motors, 27 volts; relay and contactor coils, 18-29 volts. Utilization-equipment nameplates are marked 24 volts. Voltage regulators are adjusted to hold 28.5 volts at the bus.

to decrease the pay load per pound of fuel for a given airplane and range. For example, for a 20-hour cruising range, approximately one-half pound of fuel is required to carry one pound of fixed weight over this range.¹ In addition, the engine fuel rate is approximately one-half pound of fuel per horsepower-hour. On the basis of an assumed over-all system efficiency of 50 per cent (which includes generator losses, motor losses, and distribution losses), this means that 20 pounds of fuel are required to obtain an electric-motor output of one horsepower continuously during a 20-hour flight. A gain of ten per cent in the over-all efficiency of the system thus would result in a saving of $3\frac{1}{2}$ pounds of fuel per horsepower of continuous motor load. Thus, for this case, if the increase in over-all system operating efficiency of ten per cent can be made for an increase of system fixed weight of less than $3\frac{1}{2}$ pounds per motor horsepower, a net gain can be shown. If, however, the increased weight exceeds the weight of the fuel-saving possible, the higher-efficiency equipment is not justified.

Operating Conditions

For satisfactory results, apparatus used in aircraft systems should be designed to withstand the entire range of conditions encountered in use. Many of these conditions are encountered in industrial designs, but the combination of conditions, together with the weight and space requirements, is practically unique to air-borne equipment. These conditions are as follows:

1. Ambient-temperature range.
2. Altitude range.
3. Exposure to dust, sand, salt, fungus, humidity, and corrosion.
4. Vibration.
5. Flight-attitude range.
6. Acceleration.

Numerical values can be assigned to these quantities only for specific airplanes. These values should be prescribed by the airplane designing engineer to meet his particular requirements.

For military planes, in addition to these requirements, it is desirable to design a system which has the minimum exposure and vulnerability to damage resulting from enemy gunfire. This means that damage in one part of the system should not be communicated to other parts of the system.

Driving Power for Generators

Some possible sources of driving power for aircraft generators are as follows:

1. Accessory drive shaft from main engine.
 - (a). Bolted directly to a pad on the main engine.
 - (b). Separately mounted and driven by a flexible shaft from main engine.
2. Auxiliary gas engines or gas turbines.
3. Exhaust-gas turbines.
4. Steam turbine using exhaust heat.
5. Wind-driven generators.

When a generator is bolted directly to the main engine on a suitable accessory power take-off pad, certain limitations are encountered which must be met by the generator design to enable it to fit into the space available without putting too great a strain on the engine housing. Thus the diameter, length, and bending moment (at the generator flange) are limited. Also, the generator must be designed to withstand the relatively severe vibration encountered when it is mounted directly on the engine.

These limitations dictate the maximum physical size and weight of the generator that can be mounted on a given engine.¹²

By mounting the generator separately and providing a flexible-shaft drive from the main-engine take-off pad to it, these limitations are removed, but the additional weight and space requirements of

the separate mounting and flexible shaft must be considered.

Accessory-shaft drive from the main engine, with a generator bolted directly to a take-off pad on it, is probably the most common form of drive today. This is because it provides an adequate, reliable source of power for little added weight and because it operates with good fuel economy. In a multiengine plane in which several generators are used they may be operated either isolated or in parallel. D-c generators with suitable characteristics and voltage regulators may be paralleled even though the several engines may be running at different speeds. If constant-frequency a-c generators are used, they must be driven through some form of variable-ratio drive, which is governed to maintain substantially constant speed in spite of variations in engine speed. Furthermore, conventional alternators, if operating in parallel, must run at exactly the same speed to maintain synchronism. This entails rather severe requirements for the governors and variable-ratio drives,² although this problem is simplified to a certain extent by the use of free-wheeling between the drive and the generator.

Auxiliary gas engines provide a flexible source of power that does not interfere with the main power, and can be made of any required rating. The main disadvantages to such engines, at present, are their weight, space requirements, lower fuel economy (compared with that of the main engines), and relatively poorer reliability. In comparing fuel economy for a given flight, it is necessary to take into account the efficiency of a variable-ratio drive if used, and main-engine fuel economy as compared with that of the auxiliary engines. Also, the load duty cycle has an important bearing on this calculation. Where high altitude is involved, auxiliary engines either must carry their own superchargers or be supercharged from the main-engine supercharger. Auxiliary engine-driven generators are relatively easy to operate in parallel whether alternating or direct current.

The exhaust-gas turboalternator looks promising for certain applications in which a sufficient amount of energy can be extracted from the exhaust to furnish the electrical requirements without impairing the main-engine performance, as, for example, in medium-altitude cargo planes. Generators can be operated readily in parallel when employing this type of drive. In some high-altitude aircraft in which exhaust-gas energy is

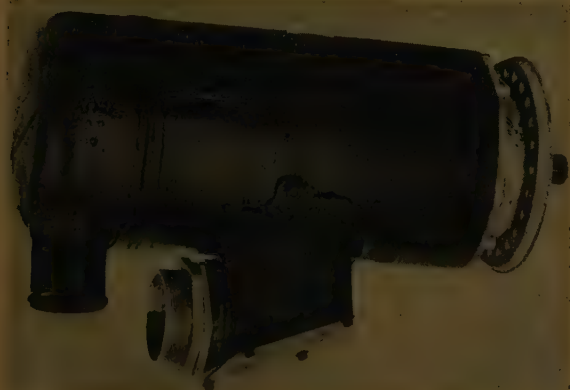


Figure 1. Side view of main-engine-mounted air-blast-cooled d-c aircraft generator
4,550/8,000 rpm; 30 volts;
300 amperes, continuous; 450
amperes, two minutes

Weight, 48 pounds; diameter,
six inches; length, 14 inches



Figure 2. Air-blast-cooled d-c aircraft generator, separately mounted, but driven from the main engine

5,400/11,200 rpm; 120 volts, $8\frac{3}{4}$ kw, continuous; $14\frac{1}{2}$ kw, five minutes; $17\frac{1}{2}$ kw, five seconds

Weight, 78 pounds; size, eight inches by eight inches by $14\frac{1}{2}$ inches long

used for supercharging cabins as well as engines, and also for deicing, there is not sufficient available energy remaining to provide driving power for a large electrical demand under all conditions of flight.

Waste heat from the exhaust can be utilized by a closed-cycle steam turbine. Such a drive naturally requires a boiler and condenser, as well as a turbine, and consequently may be difficult to justify on a weight basis. Since it operates on waste heat, however, it shows up well from the standpoint of fuel economy. For military use, a condenser having a large exposed surface would be objectionable because of its vulnerability. There are many other technical problems, such as condenser freezing at low ambient temperatures, that will have to be solved before this type of drive becomes useful in aircraft.

Wind-driven generators are used extensively on small airplanes for furnishing small amounts of power. However, they are very inefficient aerodynamically, and therefore are not competitive with other forms of drive when large amounts of power are required.

From the foregoing considerations it seems that accessory-shaft drive from main engines is the best power source available at present for the majority of large airplanes.

Types of Power Systems

The power system may take any one of a variety of forms, several of which are listed below.

1. Generate direct current and utilize direct current at substantially the same voltage, either 27 or 120 volts.
2. In some cases a dual-voltage d-c system may be used, with all the small equipment put on the 27-volt system and the larger equipment on the 120-volt system.
3. Generate variable-frequency alternating current, and rectify to utilize as direct current.
4. Generate constant-frequency constant-voltage alternating current; utilize part as alternating current, and rectify part for use as direct current.

5. Generate variable-frequency variable-voltage alternating current (voltage proportional to frequency), and utilize as generated.

6. Generate both alternating current and direct current, and utilize as generated.

7. Generate variable-frequency constant-potential alternating current; rectify and then invert to constant-frequency constant-potential alternating current.

There are many more possible combinations, but this group includes the varieties which have been used, or most seriously considered, to date.

The 27-volt d-c system has the advantages of simplicity and low hazard to operating personnel. It is satisfactory for most small and medium-sized planes. Where large amounts of electric power or large planes requiring long circuits are involved, this system becomes inadequate because of the large weight of the conductor required as a result of the limitations of conductor heating and line voltage drop. Commutation and brush wear at high altitudes are a maintenance problem, although great strides are being made toward minimizing it. This system is very widely used today.

The 120-volt d-c system overcomes the problem of excessive conductor size to a large degree, but introduces additional problems of commutation at higher voltages, particularly in small motors. It also introduces the problems of high-altitude higher-voltage switchgear and control. For energy-storage magnitude normally used for aircraft, batteries for 120-volt systems are quite heavy compared to batteries for 27-volt systems. The higher voltage is very suitable for large hoisting equipment and other similar apparatus which may be required in some cargo planes. Such systems have been used successfully and are to be included in certain aircraft now being constructed. Low voltage (27 volts) is usually required, in addition, for certain instruments, controls, and lamps (high-voltage lamp filaments do not resist vibration as well as low-voltage lamps of the same wattage).

The dual-voltage d-c system combines the advantages of the two d-c systems previously discussed with a slight added complexity.

Supplying direct current by rectifying the output of variable-frequency generators¹⁰ makes it possible to use an alternator in place of the d-c generator. The absence of a commutator permits an alternator of much greater kilowatt capacity to be built for mounting directly on the main-engine take-off pad, within the prescribed limits of bending moment and diameter. Ratings as high as 32 kw have been built within these envelope limitations, which previously were occupied by six- to nine-kw d-c generators. This system also eliminates the need for high-current brushes on the generator, and therefore minimizes the maintenance problem. However, brushes are still used on the slip rings, so that the brush problem, although considerably reduced, is not eliminated entirely. The weight of a dry-plate rectifier, or transformer and rectifier, is added but this is compensated partially by the lower weight of the alternator as compared with a d-c generator of equivalent rating. Such systems are now under intensive development.

The constant-frequency a-c system offers a suitable source of power for most loads but requires variable-ratio transmission and governors if it is to be operated from the main engines. These naturally add appreciably to the weight. However, the advantages^{1,9} of this system are sufficiently great so that now it is being given intensive development.

Use of auxiliary engines with this system eliminates the need of variable-ratio transmissions, but it is expected that such transmissions will weigh appreciably less than auxiliary engines. In general, the use of alternating current minimizes commutation and brush-wear problems, thereby decreasing maintenance. It does not eliminate these problems, however, since both exciters and slip rings may require brushes, although they do not present as difficult a problem as on completely d-c systems.

Variable frequency, with voltage proportional to frequency is satisfactory only for certain loads such as a-c torque motors. The difficulty with this system is that motors operating from it run at a speed depending upon the frequency, which varies widely. This would result in unsatisfactory performance of many devices. Other equipment, such as lights, radios, suit heaters, and so forth, normally operate at constant voltage and consequently special provision must be made for them. For these reasons, this



Figure 3. Dual-voltage d-c aircraft generator for use with auxiliary engine. The low-voltage generator also serves as a starting motor for the auxiliary engine
 4,000 rpm, 120 volts, 6.75 kw and 28.5 volts, 2.0 kw, continuous; both machines are rated for 50 per cent overload for five minutes. Weight, 125 pounds, including coupling and cooling fan; diameter, 11 inches, length, 19 1/4 inches



Figure 4. Air-blast-cooled a-c aircraft generator with direct-mounted exciter. Portion of housing and air duct removed to show exciter and collector rings. Driven from main engine at constant speed through variable-ratio transmission. Generator and transmission are mounted separately from the main engine
 6,000 rpm; three-phases 208Y/120 volts, 400 cycles, 40 kva, continuous; 60 kva, five minutes; 80 kva, five seconds; 0.75 power factor
 Weight, 80 pounds, including exciter; diameter, 9 1/4 inches; length, 17 1/4 inches

type of system is used only for certain special applications.
Dual systems a-c and d-c, with separate power sources, combine certain advantages of other systems but increase complexity. They are used for special applications.
The rectified-inverted constant-frequency constant-voltage a-e system dispenses with

the necessity for variable-ratio drives where main engines are used as the driving source. It also eliminates any need for synchronizing equipment and simplifies parallel operation. However, because of the weight of conversion equipment required and lower efficiency resulting from multiple transformation losses, this system does not seem very attractive at present.

The 27-volt d-c system is used most commonly in present-day medium and large aircraft, and it is likely to continue to be an important voltage level. Higher-voltage systems such as 120 volts direct current or 208 volts constant-frequency alternating current, supplemented by a small amount of 27-volt d-c distribution, appear promising for larger aircraft requiring greater amounts of auxiliary electric power. Much of the equipment for these higher-voltage aircraft systems is undergoing active development at the present time.

Figures 1, 2, 3, 4, and 5 show generators which have been developed for various systems.

Selection of Voltage

The selection of system operating voltage depends primarily upon the following factors, most of which can be evaluated in terms of weight.

1. Transmission distance.
2. Power to be transmitted.
3. Available utilization equipment.
4. Weight of reliable generation, distribution, and utilization apparatus.
5. Line-voltage-drop limitations.
6. Generation, distribution, and utilization of power at one voltage, insofar as possible, to avoid weight of transformers or converters.
7. Safety to personnel³ and plane.
8. Creepage, insulation,^{5,6} and arc-interruption problems.

In general, for increased power and increased transmission distances, higher voltage is desirable to minimize the weight in the power conductors. Mechanical limitations establish lower limits to wire size in aircraft wiring, and there is no gain in increasing the voltage beyond the point at which the minimum wire size can take care of a large part of the loads. As the voltage is increased, the required insulation increases, and consequently the point of diminishing returns is reached rapidly.⁸ Also, the hazard to the operator increases with increasing voltage.⁸ It is therefore, desirable, to select a practical voltage level no

higher than that which will give minimum over-all weight.
 The influence of system voltage on the weight of the power-distribution-system copper based on the same power, transmission distance, and current density is illustrated by the accompanying table:

Systems	Per Cent
27 volts, direct current, with ground return	100
120 volts, direct current, with ground return	22.5
120 volts, direct current, two-wire	45
208Y/120 volts, three-wire, three-phase, alternating current, 0.75 power factor	30

Alternating Current Versus Direct Current^{1,9}

The functions of the utilization equipment and the operating conditions will largely determine whether alternating current or direct current should be used. For example, radios normally require alternating current, whereas direct current is best adapted to many control devices.

For large high-altitude aircraft, alternating current is so promising that a great deal of development work on equipment for such systems is now in progress. The simplicity, low maintenance, safety, and light weight of a-c motors and generators tend to favor its use. Commutation and brush-wear problems are minimized. Because of commutator-design limitations, development of very high-speed motors appears more promising with alternating current. Also, certain equipment requires alternating current, which can be obtained directly from an a-c system, thereby eliminating the need for converters. Alternating current has the advantage that various desired utilization voltages can be obtained by transformers, which are lighter and simpler than d-c voltage converters.

Direct current has the advantage that generators may be driven directly from engine take-off shafts without variable-ratio constant-speed transmissions. For sizes up to 12 kw they can be mounted directly on the engine pad. Also, paralleling of d-c generators is relatively easy. D-c motors are capable of greater peak torques and starting torques than are a-c motors of the same weight. They are, also, more adaptable to speed control. Single-wire distribution, with ground return and single-pole switching, is possible with direct current on metal airplanes. Wiring weight is less, at the same voltage, because it is not necessary to transmit the wattless kilovolt-amperes

associated with alternating current at power factors other than unity. Energy storage, by use of batteries, is possible with direct current.

Sufficient data are not yet available for a complete weight comparison between a-c and d-c systems, but they are being accumulated as equipment designs are developed. Any such comparison must consider the weight of all equipment, such as generators, motors, wiring, control, variable-ratio transmissions, circuit breakers, contactors, fuses, et cetera, and also the weight of fuel required to supply the losses in the system for the duration of the flight.

Selection of Frequency if Alternating Current Is Used

The selection of frequency¹ depends to a large extent upon the type of utilization equipment used in the airplane. In general, selection should be made for minimum weight of the entire electric system which will provide satisfactory performance. It is desirable to operate motors at high speeds up to the limits of good bearing performance, since this tends to minimize equipment weight even when reduction gears are required. The frequency should be high enough to permit motor speeds in the order of 8,000 to 12,000 rpm and, yet, not so high as to require, at such speeds, too many motor poles for efficient motor design. Much of the d-c motor-driven apparatus used on present-day aircraft is designed for motor speeds of 8,000 rpm. This has been found satisfactory for continuous operation of grease-packed ball bearings. For intermittent operation, grease-packed ball bearings in small sizes operate satisfactorily up to 12,000 rpm. It is desirable to utilize these same speeds insofar as possible, to avoid unnecessary redesign of gear-reduction mechanisms, and to make use of maximum speed permitted by practical bearing design. It is desirable, therefore, to select a frequency which will provide these speeds.

The frequency should be selected so that speeds up to 24,000 rpm are not ruled out, since such speeds may be desired for the lightweight turboalternators which hold promise for the future. Such machines probably would be designed with oil-pressure lubrication on the bearings. Again, certain gyroscopic instruments may require speeds of this order.

For motors that are not geared, the frequency should be such that at least the majority of these motors can be designed with a number of poles (preferably

Figure 5. Oblique view of main-engine-mounted air-blast-cooled d-c and a-c aircraft generator

4,000/8,000 rpm; 200 amperes; 30 volts direct current. 800/1,600 cycles; single phase; ten amperes; 120 volts alternating current

Weight, 47 pounds; diameter, six inches; length, 13½ inches



four, six, or eight) which will result in the required speed with an efficient, lightweight design. The frequency should be high enough so that a sufficient number of speed steps are available in the desired motor-speed range to permit flexibility in application without requiring an excessive number of poles.

Iron-core transformers become lighter with increasing frequency within practical limits, so that this becomes a consideration in applications where many transformers are used.¹¹

There is a considerable amount of 115-volt 400-cycle single-phase a-c electronic equipment now in use in aircraft. From the standpoint of interchangeability and elimination of conversion equipment it is desirable to be able to operate this electronic equipment directly from the power system.

If too high a frequency is used, skin effect in conductors and eddy current and penetration effects in iron cores increase the weights of wiring and equipment. Except for frequencies well above 400 cycles, however, these effects are not significant for most wire sizes and equipment designs used in aircraft. For example, for all wire sizes equal to or smaller than AN-8,* the skin and proximity effects at 400 cycles increase the losses by less than one per cent. This includes the majority of wires on the 208Y/120-volt system now contemplated. For larger wire sizes, skin and proximity effects increase considerably. Thus, for AN-0 it is 11 per cent, and for AN-0000 it is 30 per cent at 400 cycles. These figures are based on minimum practical spacings with insulated aircraft cables.

Polyphase Versus Single Phase in A-C Systems

Single-phase systems offer simplicity in wiring and switching equipment. Single-phase motors require capacitors or other means of phase splitting in order to obtain starting torque. Polyphase motors

and generators are lighter than single-phase motors because they utilize available winding space more effectively.** Systems with three or more phases will transmit power with less copper than systems with a fewer number of phases. Generally there is no advantage in using more than three phases. Of course, single-phase loads can be operated from three-phase systems satisfactorily, provided they are reasonably well distributed among the phases to avoid excessive unbalance. Single-phase motors will be used only for very small incidental loads where three-phase power is available.

Types of Alternators for A-C Systems

The alternator may take any one of several forms, some of which are as follows:

1. Conventional design, with either rotating field or rotating armature.
2. Inductor alternator, having rotating salient poles excited by a stationary winding.
3. Induction alternator, having a squirrel-cage rotor.

The conventional design requires two sets of slip rings and brushes for the rotating field, and three or four sets for the rotating-armature three-phase machine, depending on whether or not the neutral is brought out. The light weight of these generators, their stability when used with direct-connected exciters, and ease of control make the conventional type of machine preferable for most cases.

The inductor alternator requires no slip rings or brushes of any kind, but its weight is from 40 to 50 per cent greater than that of the conventional type, so that it is not being developed actively for main-power generation.

The induction alternator also requires no slip rings, and can be built with a simple, sturdy rotor similar to that in a

* Army-Navy Standard Aircraft Wire Size. Approximates corresponding American Wire Gauge size.

** Except in very small sizes (1/16 horsepower and less) when it may not be practical to use three-phase windings because of space limitations.

squirrel-cage induction motor. For this type of generator, parallel operation is greatly simplified, since the machine takes its excitation from the system; consequently, synchronization and precise speed control are not required, although a variable-ratio drive is required. Where such alternators are used, however, excitation must be furnished by other synchronous machines on the system, either alternators or synchronous condensers. The weight and vulnerability of these additional necessary machines is a disadvantage. Also, the ability of the system to recover from electrical disturbances tends to be less than for systems of comparable weight using conventional generators with direct-connected exciters. The starting problem also must be given special consideration with this system, as special devices are required for this purpose.

Types of Excitation Systems for A-C Systems

If conventional alternators are used, excitation can be furnished by:

1. A direct-connected self-excited exciter.
2. Transformation and rectification from the a-c system.
3. D-c generators or batteries on the plane, if available.

The direct-connected exciter is preferred because this arrangement makes each unit independent of other units on the system. It also provides a relatively "stiff" system which will not collapse completely under excessive load or even under solid-fault conditions, since a fault or load does not reduce the available excitation. The disadvantage of this system is the added weight and space required by the exciter, and the fact that brushes and commutator are present on the exciter. However, since the energy requirements for the exciter are relatively small, this does not appear to be a serious problem. A direct-connected exciter also results in lighter voltage-regulating equipment, since only exciter field current need be regulated, and standard voltage regulators that already have been developed for aircraft can be used with only slight modifications.

Excitation from rectifier supply must depend either upon residual in the alternators or upon the presence of an independent d-c system for initial build-up. A collapse of the a-c system through a sustained solid three-phase fault will mean a loss of excitation and, consequently, the inability to burn the fault

clear. It also makes a system that is less stiff and has a maximum current point beyond which both the voltage and excitation will collapse unless the overload or fault is removed very quickly. This system introduces starting problems, particularly at low ambient temperatures at which the rectifier resistance increases. If high residual is incorporated to assist in starting, the regulator range required is increased considerably.

Excitation from an independent d-c system has the disadvantage that damage in the d-c system (a fault, for example) is communicated immediately to the a-c system as a loss of excitation, thereby tending to depress the a-c voltage also. It also requires heavier nonstandard voltage-regulating equipment compared with that for direct-connected exciters.

Manner of Grounding

Most 27-volt d-c systems are solidly grounded to eliminate one wire in metal planes. This not only reduces the weight of wiring but also the exposure to hazards such as gunfire. One disadvantage of grounding is that any energized conductor accidentally coming in contact with the metallic skin of the plane constitutes a fault on the system.

Higher-voltage d-c systems probably also will be grounded to eliminate one wire. While a perfectly isolated system would involve less hazard to operating personnel than a grounded system, there is always in practice, a certain amount of capacitance and leakage between conductors and ground and also the possibility of accidental grounds, so that it is doubtful whether grounding significantly affects electric-shock hazard.

When both voltages of a dual-voltage d-c system are grounded, a third voltage is made available, which is either the sum or difference of the other two voltages, depending on whether like or unlike polarities on the two systems are grounded.

Some of the usual reasons for a-c system grounding, such as protection against transient overvoltages (on systems above 600 volts) and possible improvement of lightning-arrester protection for overhead transmission systems, are not important in aircraft.

Grounding of aircraft systems has the advantage that accidental faults either are cleared immediately or otherwise detected so that faults are not likely to go unnoticed. Ground detectors can be used, of course, with an ungrounded system, but they will not indicate the location of the fault. Accidental

grounds, in an ungrounded system, which are not detected constitute a hazard, since the next ground on another conductor puts a fault on the system. Grounding the neutral of a three-phase a-c system on a metal airplane provides the equivalent of a four-wire system, so that single-phase loads can be operated conveniently at line-to-neutral voltage. Furthermore, if polyphase motors are operating on the system and their neutrals are grounded, they will continue to operate reasonably well if one circuit is accidentally open-circuited (by enemy gunfire, for example). This is considered to be an advantage on certain types of equipment for military planes.

Grounding of the neutrals of a-c generators increases the line-to-ground fault current of the system. If the utilization equipment is ungrounded, this ground fault current can be limited to any desired value by a suitable resistor or reactor in the generator neutral. However, in cases where the motors in the utilization equipment have solidly grounded neutrals, such a current-limiting device does little to limit the line-to-ground current. See Figure 6.

Whereas grounding the neutral solidly increases the fault currents which must be handled by the switchgear, it also prevents displacement of the neutral so that the switch voltage is reduced; hence the weight of switching equipment is not necessarily increased. This is shown by Figure 7. Higher ground-fault currents speed up the "burning clear" of ground faults and make it more difficult to obtain a "welded" fault.⁴ They shorten the fault clearing time for fuses which may be used in the circuits.

Grounding of one phase of a three-phase a-c system has been given consideration, but is not being planned for any specific projects to date. The weight of one wire is saved, of course by this means, and switches may be only two pole. However, line-to-neutral voltage is not available then, switchgear must handle 73 per cent higher voltage per pole, electric-shock hazard is somewhat increased by the higher line-to-ground voltage, and an increase of radio and interphone interference resulting from the presence of unbalanced fields may be introduced.

Power-Factor Correction

Capacitors frequently are used for power-factor correction in industrial a-c systems. The benefits are reduction in line losses, reduced wire size to transmit a given amount of power, and increased

power available from a given-size generator. In higher-frequency a-c systems such as the 400-cycle system, the weight of capacitors required per kilovolt-ampere of correction is substantially less than that in 60-cycle systems of the same voltage. Capacitor weights of the order of 1 1/4 pounds per kilovolt-ampere, in sizes of one-half kilovolt-ampere and larger, are now available for 208-volt 400-cycle systems, and future developments may reduce this considerably.

In spite of these relatively low weights for corrective capacitors for 400-cycle a-c systems, it is doubtful if they will have widespread application in aircraft, because the lines are relatively short and the loading intermittent. Preliminary calculations on certain systems indicate that the savings in wire weight, losses, and generation are offset by the weight of the capacitors. Such a calculation can be made for any given system to determine whether or not power-factor correction is justified. In general, the lower the power factor, the more effective are the capacitors, so that for some very low-power-factor apparatus they can be justified. It usually does not pay to correct to unity power factor, however.

In addition to the weight and economy, there are certain other factors that should be considered in any particular case in determining whether or not power-factor correction is desirable. The capacitors occupy a certain amount of space and, therefore, tend to increase the vulnerability of the system to gunfire, for example, and to accidental fault. In addition, where parallel operation is involved, the system stability is reduced if full advantage is taken in reduction of possible generator size.

Parallel Versus Nonparallel Operation

When several generators are used, parallel operation provides certain advantages and has certain drawbacks. The most important of these are given in the following tabulation, and apply to both a-c and d-c systems.

ADVANTAGES

1. Greater motor-starting capacity.
2. Reduction of time and magnitude of voltage disturbances from faults, motor starting, or loss of generation.
3. More effective use of spare capacity, so that smaller or fewer generators can be used without excessive load-transfer switching.
4. Greater ability to burn faults clear.⁴
5. Continued operation of load equipment following engine or generator failure does

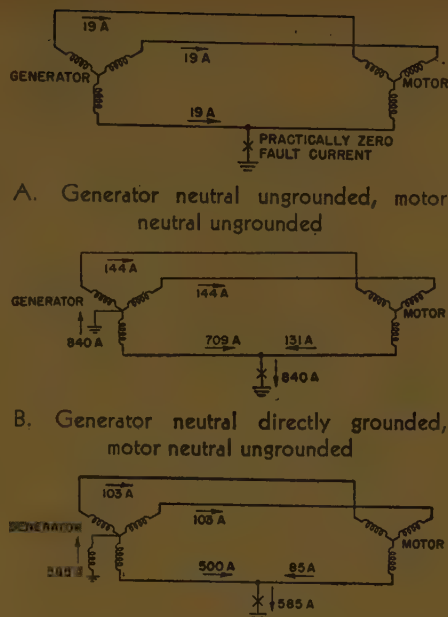


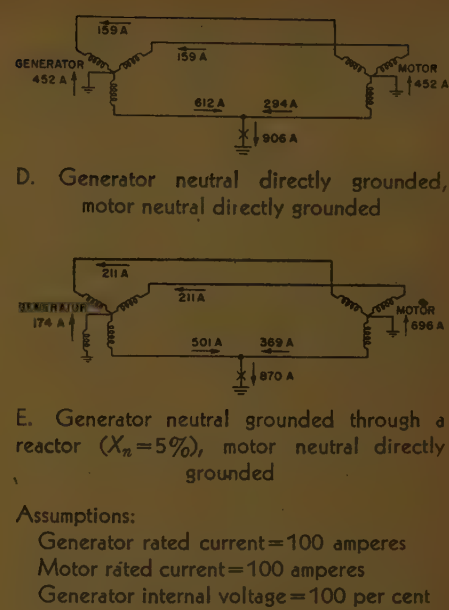
Figure 6. Effect of neutral grounding and neutral impedance on line-to-ground fault current

not require any automatic transfer equipment nor any immediate attention from the operator.

DISADVANTAGES

1. Increases weight and complexity of control, especially for alternating current. Equipment for synchronizing is required for paralleled a-c systems. Constant-speed transmissions for a-c systems require accurate governing if generators are to be paralleled (with auxiliary-engine drive this problem is not so severe). For d-c generators, voltage regulators must control within very close limits to permit satisfactory parallel operation. Furthermore, equalizing circuits must be designed and maintained carefully, especially if a large number of generators is used.
2. Routine monitoring of load balance and (for alternating current) reactive kilovolt-ampere balance may be required.
3. Faults and other disturbances affect entire electric system.
4. Heavier switchgear is required because of the greater fault currents available.
5. Co-ordination problems relating to circuit protective equipment are more exacting because of the possibility of variable generation, and the higher currents involved.

No general rule can be made since the selection here depends, to a large extent on the type of utilization equipment and the nature of the operations involved. Both parallel and nonparallel operation have been used successfully in airplanes. A-c systems which are subject to loss of synchronism through fault or other disturbances should be designed so that they can operate either parallel or nonparallel.



Assumptions:

- Generator rated current=100 amperes
- Motor rated current=100 amperes
- Generator internal voltage=100 per cent

Reactances	Generator (Per Cent)	Motor (Running Light) (Per Cent)
Positive sequence, X_1	20	500
Negative sequence, X_2	20	20
Zero sequence, X_0	5	5

At present, considerable development work is being pursued in order to establish the practicability and performance requirements of parallel operation of aircraft alternators from engine take-off drives using variable-ratio transmissions.

Synchronizing Methods for Paralleling A-C Generators²

If the system selected is alternating current, and parallel operation is desired, the question of how best to synchronize the generators is introduced. There are several methods available. These are:

1. Automatic synchronizing, with full voltage on both running and incoming machines.
2. Automatic synchronizing, with reduced or zero voltage on the incoming machine.
3. Manual synchronizing, with either full, reduced, or zero voltage on the incoming machine.
4. Random manual synchronizing at full voltage.

It is probable that purely random synchronizing, without any attempt to match the phase angles of the generators before switching them together, will cause undue momentary disturbance to the system voltage. At present, considerable development is in progress on equipment for fully automatic synchronizing, which will parallel a-c generators with practically no resulting disturbance. However, this involves appreciable added

weight and complexity in control equipment, so work is being done also on simpler and lighter automatic equipment, which will connect generators together with little or no excitation on the incoming machine, building its excitation up immediately after switching. This will cause some disturbance to the system voltage, but may be acceptable in some cases. In general, automatic synchronizing is expected to be preferable to manual means, since manual synchronizing requires considerable attention and skill on the part of the operator.

Size and Number of Generators

The number of generators is selected by considerations of vulnerability and amount of stand-by power desired for emergency use. Generators should be distributed among engines as far as is practicable, so that loss of one engine will not cause too great a loss of generation. From the standpoint of weight economy, it is important that the airplane not be burdened with excessive generating capacity. Stand-by capacity of 100 per cent is considered to be the upper limit, even for military combat planes.

It is desirable to select generators which individually are large enough to start the largest single load (or group of loads which must be started simultaneously). This may seem unnecessary

when parallel operation is used, but is a desirable feature, since operation from one generator may be required in an emergency.

The electric loads can be grouped into two main categories, namely:

1. Those essential to flight.
2. All other loads.

These other loads have varying degrees of importance in different planes but they are always subordinate to those in classification 1. In the selection of the amount of stand-by power, this division and the degree of importance of other loads is an important consideration, since service to loads of lesser importance may be discontinued in an emergency. It is desirable, of course, to lay out the system so that the amount of generation left on a crippled plane that can still fly will be sufficient to bring the plane back safely.

In totaling the electric load on an airplane, duty cycle and time of operation are important considerations, since many of the loads are highly intermittent in nature. The peak load requirement must be met with suitable stand-by, of course. Short-time overload ratings are given on aircraft generators to permit proper selection for such conditions.

Use of Auxiliary-Engine-Driven Generators to Supplement Main-Engine-Driven Generators

An auxiliary set, either hand- or battery-started, is of value for ground operations such as electrical testing and starting the main engines.

Such a set usually is not supercharged. However, at low altitudes it could be used to furnish some essential power in an emergency, provided that the unit is installed in such a manner that it can be started after hours of flight at extremely low temperatures.

In cases where the weight of such a unit might be considered excessive, it can be treated as disposable load, provided that the airplane always is to be based where auxiliary ground power is available or a battery is used that will handle all essential ground operations, such as engine starting in cases where electric starters are used.

Satisfactory, small, independent, lightweight superchargers, suitable for use with small auxiliary engines in aircraft which must operate at high altitude, and which are subject to sudden changes of load, have not yet appeared. However, it is possible to utilize the first stage (turbine- or gear-driven) of the main-engine

supercharger for this purpose. Another possibility is to utilize air from the cabin supercharger (or cabin waste air), if available in sufficient quantity to meet the requirements, and if the supply is dependable under all conditions of operation.

Use of an Auxiliary D-C System With Main A-C Power System

Certain control functions, instruments, and other small electric loads are handled most economically from a low-voltage d-c system and, consequently, it seems desirable to maintain such a system even in cases where the main power is alternating current. Such a system may be derived from the main a-c system by suitable transformation and rectification. It may or may not have a battery. If no battery is used, it is important to arrange the circuits in such a manner that the a-c system can be started, preferably without the use of auxiliary ground power.

Distribution-System Design

The fundamental principles of good distribution-system design are the same for all types of systems. Protective equipment for generators, busses, lines, and utilization equipment for d-c and a-c systems, of all voltages used so far in aircraft, are available or are being developed. It is beyond the scope of this paper to discuss the various means and devices for insuring reliable distribution-system performance with minimum weight. This weight should be evaluated in each specific case when selection among types of power systems is to be made.

Conclusions

There are many conflicting requirements for different applications, but the need for higher-voltage higher-power systems has required industry to develop apparatus rapidly to meet this demand. Consideration of the previously enumerated conditions and requirements has resulted in the selection of the 208Y/120-volt 400-cycle three-phase grounded-neutral system as one standard for a-c systems in aircraft. This choice represents a compromise of the many factors involved. All parts of these systems are now undergoing intensive development. These developments entail an enormous amount of engineering and development work, as practically every piece of apparatus in the generation, distribution, and utilization systems has to be designed especially for 400 cycles

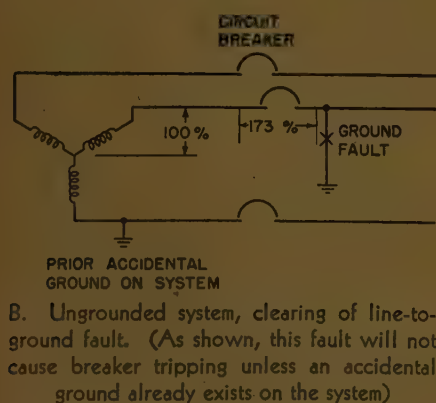
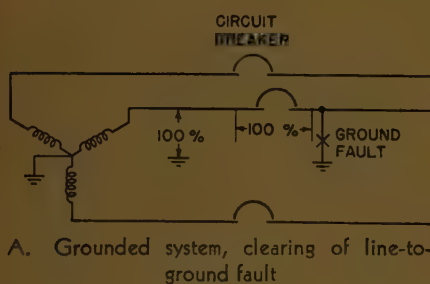


Figure 7. Effect of grounding on recovery voltages. (Voltages are given in per cent of normal line-to-ground voltage)

and aircraft use, which requires lightweight, vibration-resistant designs operable at high altitude.

The selection of 208Y/120 volts, 400 cycles, and three phases as a voltage and frequency level for a-c systems in aircraft appears to be a particularly happy choice, in that this voltage is high enough to transmit the required amounts of electric power economically over the distances required by the largest planes and high enough for the largest amounts of auxiliary electric power in any planes now being designed or likely to appear in the near future. This voltage is low enough so that no unusual difficulties are experienced in switching, even at high altitudes. It is below the range where corona at high altitude becomes troublesome.⁶ Again, it is low enough so that it does not constitute a very serious hazard to operating personnel from accidental contact. Four hundred cycles is somewhat less hazardous in this respect than 60 cycles.³

A considerable amount of equipment in military planes is now served by 115-volt 400-cycle single-phase inverters or dynamotors operating from the 27-volt d-c system. This apparatus can be served directly from the 208Y/120-volt 400-cycle system, which probably will be adjusted to hold about 205 volts at the generator bus so that the utilization-equipment voltage will be about 200Y±15. In this way, no transformers

will be required to serve this apparatus, and the need for dynamotors or inverters will be eliminated, with a consequent saving in weight.

The proposed system will retain a relatively small 27-volt d-c system derived from the main a-c system for control, instruments, and other small loads as required. Generators will be of the conventional type with direct-connected exciters.

Some work has been and is being done on 120-volt d-c equipment. It is probable that dual-voltage d-c systems (27 and 120 volts) will make their appearance in medium-altitude cargo or transport airplanes where commutation and brush problems are not so severe and the equipment is of the nature of hoisting equipment or similar apparatus for which this voltage is well adapted.

Thus the aircraft industry will have the following voltage levels for which apparatus already is available or is being designed:

1. For very small planes, such as private planes, 6- or 12-volt d-c systems.
2. For small and medium-sized planes, 27-volt d-c systems.
3. For large medium-altitude cargo or transport planes, dual-voltage (27- and 120-volt) d-c systems.
4. For large high-altitude long-range planes, 208Y/120-volt three-phase 400-cycle a-c systems.

These voltage levels will probably meet the needs of the aircraft industry for some time to come.

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Starting Windings for Single-Phase Induction Motors

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Synopsis: Methods are given to enable the design engineer to determine the best starting winding and the best capacitor, reactor, or resistor required to meet any specified requirements. The methods given have been in actual use by design engineers for over 12 years, and are as useful today as they were when developed. Simple circle diagrams depict graphically the principles involved in the method. Some practical observations, based on experience, are given. A calculation form, with sample calculations, is also included.

CALCULATION METHODS given in this paper supply the designer with a tool for computing the starting performance of any given winding; they also enable him to determine the particular auxiliary winding best suited to meet any given set of requirements. In this paper use is made of the equivalent-circuit concept so popular in technical writing. Also, use is made of the concepts of *open-circuit reactance* and *short-circuit reactance*, introduced by Branson in 1912,⁴ followed by Kron,⁵ Boothby,¹ Puchstein and Lloyd,⁶ Himebrook,⁷ Trickey,⁸ and by the author in previous papers.^{2,9}

Locked-Rotor Impedance of a Single Winding

A necessary preliminary to the determination of starting performance is the determination of the locked-rotor impedance. Very roughly, the locked-rotor impedance is

$$\hat{Z} = (r_1 + r_2) + j(x_1 + x_2) \quad (101)$$

This simple relationship usually is not accurate enough for fractional-horse-power motor design. A more accurate expression, given as equation 2 in Appendix I, is

$$\hat{Z} = (r_1 + r_2 C_r) + jX_{CR} \quad (102)$$

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The coefficients C_r and C_R are defined in equations 9 and 10 and plotted in the form of curves in Figure 2. It will be observed that the apparent rotor resistance is always less than the actual, while the apparent short-circuit reactance is always greater than the ideal. In the derivations that follow, the apparent impedance, as defined above, is used consistently.

Starting-Torque Equation for Single-Phase Induction Motors

C. R. Boothby¹ gave the following equation for the starting torque of a single-phase induction motor with an auxiliary winding. Expressed in the notation of this paper, and with one modification, his equation is

$$T_s = \frac{1.88p}{f} K r_{2m}' I_m I_a \sin(\theta_m - \theta_a) \quad (\text{ounce-feet}) \quad (103)$$

The modification from this original equation is the use of the apparent rotor resistance, r_{2m}' , instead of the actual rotor resistance, r_{2m} . (See Table I.) Morrill³ has given a more rigorous derivation of the starting-torque equation; equation 14 of his paper is exactly reducible to equation 103. This starting-torque equation is applicable to all types of single-phase induction motors having two windings in space quadrature; it is the basis for the remainder of this paper.

Starting Windings for Split-Phase Induction Motors

The design of the main or running winding usually is fixed by considerations of efficiency and breakdown torque. The

problem generally is to find the best possible companion starting winding; in this connection, considerable help will be given by Figure 3, which shows in a graphical manner how various changes in auxiliary winding affect the starting torque and line current.

The magnitude and phase position of the locked-rotor current of the main winding is computed from equation 102 and laid out in Figure 3 as OA . A certain number of turns and distribution of the starting winding is assumed, fixing the reactance, X_a' . The problem now is to determine the optimum resistance for this assumed starting winding. The semicircle AGB is constructed with $AB = E/X_a'$. Now, take any point on this semicircle, C , for example; the line AC represents the magnitude and phase position of the auxiliary-winding current, I_a , for some as yet unknown value of R_a and the assumed value of X_a' . In other words, the semicircle is the locus of the end of the vector I_a as R_a is varied, all other quantities remaining constant. The line current is OC or the vector sum of the main- and auxiliary-winding currents. The starting torque is proportional to the length of CK , since

$$CK = I_a \sin(\theta_m - \theta_a)$$

The maximum starting torque that can be obtained by varying R_a and leaving all other terms fixed occurs when CK is a maximum in length. This condition is fulfilled by point D on the diagram, where D is midway between A and G on the arc. The maximum starting torque per ampere of line current is obtained when the ratio CK/OC is a maximum, which occurs when the line OC is tangent to the semicircle. In the figure, C is actually the point for maximum starting torque per ampere.

This diagram shows a considerable increase in line current between points C and D for an almost negligible gain in starting torque. The diagram is most helpful in visualizing the factors involved and their interrelationships. It is not recommended as a routine design procedure; algebraic equations are better

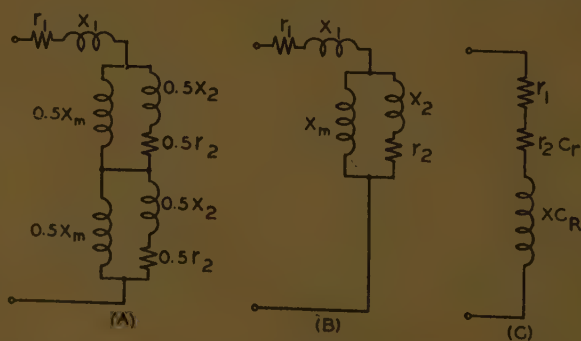


Figure 1. Equivalent circuit of a single-phase induction motor at standstill (revolving-field theory)

ited to this purpose. Such equations may be developed from the diagram. First, two distinct starting windings will be recognized: a *maximum-torque winding* as indicated by point *D*, and a *maximum-torque-per-ampere winding*, as indicated by point *C*.

Maximum-Torque Windings for Split-Phase Motors

For the maximum-torque winding

$$\frac{AD}{AG} = \frac{1}{2}$$

therefore, by plane geometry

$$\angle DAH = \theta_a = \frac{\theta_m}{2} \quad (104)$$

By trigonometry

$$\cot \theta_a = \cot \frac{\theta_m}{2} = \frac{1 + \cos \theta_m}{\sin \theta_m} = \frac{1}{\sin \theta_m} + \cot \theta_m$$

or

$$\frac{R_a}{X_a'} = \frac{R_m + Z_m}{X_m'} \quad (105)$$

or

$$R_a = \frac{X_a'}{X_m'} (R_m + Z_m) \quad (106)$$

The total resistance in the primary of the starting winding is

$$r_{1a} = R_a - r_{2a}' \quad (107)$$

Equation 106 gives the total value of resistance that must be used in the primary winding to obtain a maximum-torque winding as shown by point *D* in Figure 3.

At the AIEE North Eastern District technical meeting in Rochester, N. Y., in 1931, P. H. Trickey presented a student paper on starting windings in which, by differentiating a form of equation 103 and finding the value of r_{1a} to give a maximum T_s , he found that

$$r_{1a} = K^2(r_{1m} + Z_m) \quad (108)$$

which is substantially equivalent to equation 106. The comparison is interesting. Trickey's student paper goes on to investigate the maximum-torque winding quite extensively. Unfortunately, however, this winding is seldom the best one to be used, as it results usually in the use of more copper in the starting winding than necessary and sometimes results in low pull-up torque.

Maximum-Torque-Per-Ampere Windings for Split-Phase Motors

Point *C* in Figure 3 defines a maximum-torque-per-ampere winding. It is shown in Appendix II that the value of R_a , corresponding to point *C*, is

$$R_a = \frac{R_m X_a' + Z_m \sqrt{X_a' (X_m' + X_a')}}{X_m'} \quad (109)$$

Equation 109 gives the total value of resistance that must be in the auxiliary

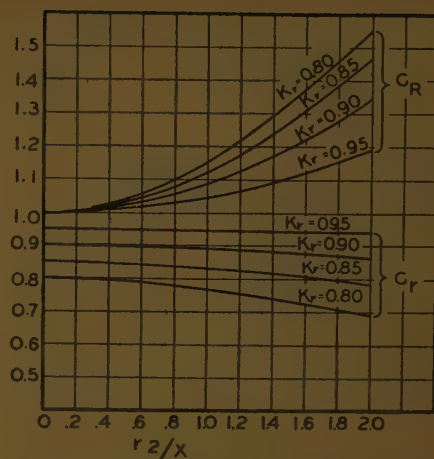


Figure 2. Variation of C_R and C_r with change in motor-design constants

phase to obtain a maximum-torque-per-ampere winding; the total resistance that must be used in the primary winding is found by subtracting r_{2a}' , as done in equation 107.

Calculation of a maximum-torque-per-ampere winding using the form of Figure 6 can be simplified by rewriting equation 109 in the form

$$X_m' R_a - R_m X_a' = Z_m \sqrt{X_a' X_{ma}'} \quad (109a)$$

More useful than the above are equations giving the required values of R_a and X_a' in terms of the desired locked-rotor current, since the latter quantity usually is specified. For a maximum-torque-per-ampere winding designed so that the total locked-rotor current in the line is I_L , it is

Table 1. Motor Constants for Locked-Rotor Conditions

	Windings Only		Windings With External Impedance in Series		
	Main Winding	Auxiliary Winding	Auxiliary Winding With Resistor	Auxiliary Winding With Capacitor	Main Winding With Reactor
1. Applied volts	E	E	E	E	E
2. External impedance	O	O	Z_r	Z_c	Z_R
3. Real component of external impedance	O	O	R_r	R_c	R_R
4. j component of external impedance	O	O	X_r	X_c	X_R
5. Rotor resistance, referred to primary winding concerned	r_{2m}	r_{2a}	r_{2a}	r_{2a}	r_{2m}
6. Apparent rotor resistance	$r_{2m}' = C_r r_{2m}$	$r_{2a}' = C_r r_{2a}$	$r_{2a}' = C_r r_{2a}$	$r_{2a}' = C_r r_{2a}$	$r_{2m}' = C_r r_{2m}$
7. Resistance of primary winding	r_{1m}	r_{1a}	r_{1a}	r_{1a}	r_{1m}
8. Real component of total impedance	$R_m = r_{1m} + r_{2m}'$	$R_a = R_{1a} + r_{2a}'$	$R_{ar} = R_a + R_r$	$R_{ac} = R_a + R_c$	$R_{mR} = R_m + R_R$
9. Ideal reactance	X_m	X_a			
10. Apparent reactance, or j component of total impedance	$X_m' = C_R X_m$	$X_a' = C_R X_a$	$X_{ar}' = X_a' + X_r$	$X_{ac}' = X_a' + X_c$	$X_{mR}' = X_m' + X_R$
11. Total impedance	$Z_m = \sqrt{R_m^2 + X_m'^2}$	$Z_a = \sqrt{R_a^2 + X_a'^2}$	$Z_{ar} = \sqrt{R_{ar}^2 + X_{ar}'^2}$	$Z_{ac} = \sqrt{R_{ac}^2 + X_{ac}'^2}$	$Z_{mR} = \sqrt{R_{mR}^2 + X_{mR}'^2}$
12. Current in one phase	$I_m = E/Z_m$	$I_a = E/Z_a$	$I_{ar} = E/Z_{ar}$	$I_{ac} = E/Z_{ac}$	$I_{mR} = E/Z_{mR}$
13. Angle of lag of current behind the voltage	θ_m	θ_a	θ_{ar}	θ_{ac}	θ_{mR}
14. Defining equation for angle of lag	$\tan \theta_m = \frac{X_m'}{R_m}$	$\tan \theta_a = \frac{X_a'}{R_a}$	$\tan \theta_{ar} = \frac{X_{ar}'}{R_{ar}}$	$\tan \theta_{ac} = \frac{X_{ac}'}{R_{ac}}$	$\tan \theta_{mR} = \frac{X_{mR}'}{R_{mR}}$

shown in Appendix II that the starting winding has the following constants:

$$R_a = \frac{R_m + Z_m(I_L/I_m)}{(I_L/I_m)^2 - 1} \quad (110)$$

$$(25)$$

and

$$X_a' = \frac{X_m'}{(I_L/I_m)^2 - 1} \quad (111)$$

$$(18)$$

where I_m = locked-rotor current in main winding only.

Of the equations given so far, 110 and 111 are the most useful. They completely specify a starting winding that gives the maximum starting torque per ampere of line current for a given main winding and specified value of total locked-rotor current. In using these equations, however, the current density in the starting windings must be checked, for sometimes these formulas lead to an overworked starting winding.

In general, the maximum-torque-per-ampere winding results in less weight of starting-winding copper and works the starting winding harder than the maximum-torque winding. Practical windings often are a compromise between the two, and generally favor the former, as far as possible.

Alternate Formula for Starting Windings for Split-Phase Motors

The circle diagram of Figure 3 is based upon the assumption that R_a is the variable and all other factors remain constant. H. E. Ellis has derived an interesting equation from equation 103, assuming X_a' to be the variable and all other factors remain constant. He assumed

$$K \propto \sqrt{(X_a'/X_m)} \quad (112)$$

K thus becomes a variable in his analysis.

Equation 103 can then be rewritten

$$T_s = \text{constant} \left(\sqrt{\frac{X_a'}{X_m}} \cdot \left(\frac{X_m' R_a - R_m X_a'}{Z_m(R_a^2 + X_a'^2)} \right) \right) \quad (113)$$

$$\frac{dT_s}{dX_a'} = X_a'^{-3} - 3X_a'^{-2} \left(\frac{X_m' R_a}{R_m} \right) - \frac{3X_a' R_a^2 + \frac{X_m' R_a^3}{R_m}}{R_m} = 0 \quad (114)$$

Solving for X_a' , one finds that the only practical root is

$$X_a' = \frac{R_a}{R_m} \left(X_m' - 2Z_m \sin \frac{\theta_m}{3} \right) \quad (115)$$

An excellent procedure is to calculate R_a from equation 110, and X_a' from equation 115, in place of equation 111. This procedure is perhaps the best but, of

course, the current density in the starting winding has to be watched.

Resistance-Start Motors

A resistance-start motor differs from a split-phase motor only in that an external resistance is used in series with the starting winding. In such a case, R_a as used

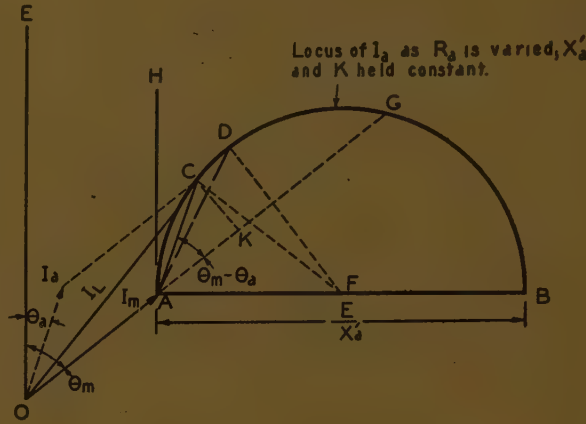


Figure 3. Starting-torque diagram for a split-phase motor

in the preceding expressions, must be assumed to include the resistance of the external resistor as well as the resistance of the motor windings.

Capacitor-Start Motors

The locked-rotor conditions of a capacitor-start motor are illustrated in Figure 4.* Both main and capacitor windings are assumed. The magnitude and phase position of the main-winding current I_m is constructed as OA . A value of capacitance has been assumed, and the capacitor-phase current I_a is laid out similarly as AC . Now, if we make the assumption that R_{ac} , the total resistance in the capacitor phase, remains constant, the locus of point C , as the external microfarads vary, will be the semicircle shown having a diameter of E/R_{ac} . This assumption is not strictly correct, for R_{ac} will vary slightly as the microfarads are changed (because R_c does), but it leads to convenient and useful formulas, and the slight variation in R_{ac} with microfarads can be taken into account, as will be shown later.

The point for maximum starting torque is D , found by drawing a tangent parallel to OA . It is shown in Appendix III that the maximum starting is obtained when

$$-X_{ac}' = \frac{R_{ac}}{R_m} (Z_m - X_m') = \frac{R_{ac} R_m}{Z_m + X_m'} \quad (116)$$

$$(28)$$

* Some time after these analyses were made, it was discovered that W. J. Morrill had shown a similar diagram as Figure 4 of his paper,⁸ though he did not develop it to the extent done in this paper.

(X_{ac}' from equation 116 is always a negative number.)

The reactance of the external capacitor is simply

$$X_c = X_{ac}' - X_a' \quad (117)$$

where X_{ac}' is found from equation 116. (Since X_{ac}' and X_c are both negative, $-X_c$ is the arithmetical sum of

X_{ac}' and X_a' .) Equation 116 is similar to the one given by Boothby,¹ who derived his expression by a different method. The value of microfarads obtained from equation 116 may be called *maximum-torque microfarads*. Almost without exception, this value of microfarads is too great for a practical capacitor-start motor.

A much better value of microfarads is that which gives the maximum starting torque per ampere, as indicated by point C in Figure 4. In Appendix III it is shown that the starting torque per ampere is a maximum when

$$X_{ac}' = \frac{X_m' R_{ac} - Z_m \sqrt{R_{ac}(R_m + R_{ac})}}{R_m} \quad (118)$$

$$(36)$$

Thus, the procedure of finding the number of microfarads that will yield the maximum starting torque per ampere of line current when the main winding is fixed, is as follows:

- Compute the algebraic value of X_{ac}' from equation 118. The result will be a negative quantity.
- Compute the external capacitive reactance from equation 117.
- Microfarads = $\frac{10^6}{2\pi f(-X_c)}$
- If the value of microfarads so found is such that its effective resistance, R_c , is considerably different from the assumed value of R_c , steps (a), (b), and (c) can be repeated using the correct value of R_c to obtain R_{ac} . This refinement generally is unnecessary, however.

Calculation of microfarads for maximum starting torque per ampere using

The form of Figure 6 can be simplified by rewriting equation 118 in the following form:

$$X_m' R_{ac} - R_m X_{ac}' = Z_m \sqrt{R_{ac} R_{mac}} \quad (118a)$$

Equations are developed in Appendix III for R_{ac} and X_{ac}' in terms of the constants of the main winding and the locked-rotor line current. These expressions are

$$X_{ac}' = \frac{X_m' - Z_m(I_L/I_m)}{\left(\frac{I_L}{I_m}\right)^2 - 1} \quad (120)$$

$$R_{ac} = \frac{R_m}{\left(\frac{I_L}{I_m}\right)^2 - 1} \quad (121)$$

These equations are similar to 110 and 111 for split-phase motors. However, the author has not found them so useful as their companion formulas for split-phase motors. One reason is that usually it is practicable and more advantageous to use a lower value of R_{ac} than equation 121 indicates. More important, though, is the fact that neither equation 120 nor 121 gives any clue as to the proper number of turns to use in the auxiliary winding. Hence these two equations are of an interest more academic than practical.

Best Winding for a Capacitor-Start Motor

Selection of an auxiliary winding and capacitor for a capacitor-start motor requires the exercise of judgment and experience that cannot be expressed wholly in the form of equations. Attention must be paid to the voltage across the capacitor, not only for the locked-rotor condition, but also for all speeds up to switch-operating speed. Usually it

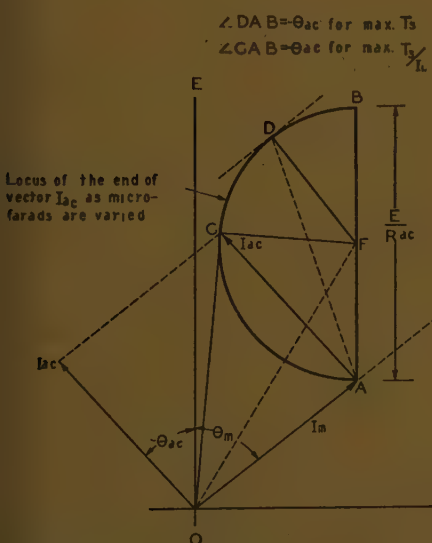


Figure 4. Starting-torque diagram for a capacitor-start motor

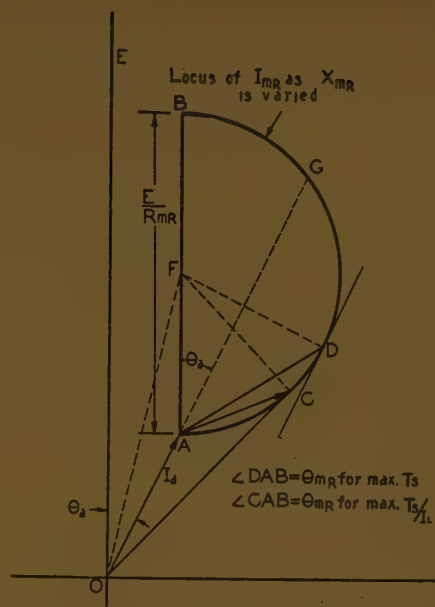


Figure 5. Starting-torque diagram for a reactor-start motor

will be necessary to make a number of trial designs before selecting the best one to meet the conditions specified. One procedure is to assume a starting winding, compute the microfarads for maximum starting torque per ampere from equation 118, then with this value of capacitance calculate starting torque, line amperes, and capacitor volts. If the starting torque is low, it may be necessary to do some combination of the following:

1. Increase the number of microfarads.
2. Increase the resistance of the rotor.
3. Increase the number of turns in the auxiliary winding.

If the capacitor voltage is high, it may be necessary to do some combination of the following:

1. Increase the microfarads.
2. Increase the resistance of the auxiliary winding.
3. Increase the rotor resistance.

If the locked-rotor current is high, it may be necessary to do one or the other of the following:

1. Increase the rotor resistance.
2. Increase the number of turns in the auxiliary winding and decrease the number of microfarads.
3. Reduce the breakdown torque by increasing the turns of the main winding.

Use of the microfarads for maximum starting torque from equation 116, as shown by point D in Figure 4, may result in some of the aforementioned difficulties; more microfarads almost certainly will give trouble. It is best, usually, to work between points C and D in Figure 4,

which means that the value of capacitance chosen should lie between the values given by equations 116 and 118.

Reactor-Start Motors

Reactor-start motors are generally similar to split-phase motors except that, during the starting period, an external reactor is connected in series with the main winding. A circle diagram of the starting conditions of such a motor is given in Figure 5. In Appendix IV, it is shown that the external reactance for maximum starting torque is

$$X_R = \frac{R_a R_{mR}}{Z_a - X_a'} - X_m' \text{ or } \frac{R_{mR}}{R_a} \times (Z_a + X_a') - X_m' \quad (122)$$

Likewise it is shown that the external reactance for maximum starting torque per ampere is

$$X_R = \frac{X_a' R_{mR} + Z_a \sqrt{R_{mR}(R_a + R_{mR})}}{R_a} - X_m' \quad (123)$$

Locked-Rotor Line Current for Motor With Auxiliary Winding

If two impedances, Z_m and Z_a are connected in parallel to a voltage E , the resultant line current, by Kirchhoff's laws, is

$$I_L = \frac{E(Z_m + Z_a)}{Z_m Z_a} = I_m \frac{(Z_m + Z_a)}{Z_a} = I_m \frac{Z_{ma}}{Z_a} \quad (124)$$

or

$$I_L = I_m \frac{Z_{ma}}{Z_a} \quad (125)$$

where

$$Z_{ma} = \sqrt{(R_m + R_a)^2 + (X_m + X_a)^2} \quad (126)$$

Equation 125 is a most convenient expression for calculating the line current. It appears in modified forms in equations 19, 35, and 48.

A Practical Calculating Form

For determination of the best auxiliary windings and best winding and capacitor combinations, the calculating form shown in Figure 6 was devised with the assistance of H. E. Ellis; it has been of enormous practical value. It was designed for both split-phase and for capacitor-start motors. When all the constants of both windings (and external capacitor, if any) are known, the calculations are made in the order listed except that three

CALCULATION #			1	2	3	4	5	6	7	8
(20) = EITHER SIN (16) (19) OR (5) x (13)										
	RESISTANCE	CAPACITOR								
1	Γ_{1m}	Γ_{1m}	1.47	1.47	1.47					
2	$\Gamma_{2m'}$	$\Gamma_{2m'}$	2.67	2.67	2.67					
3	R_m	R_m	4.14	4.14	4.14					
4	$X_{m'}$	$X_{m'}$	3.72	3.72	3.72					
5	Z_m	Z_m	5.57	5.57	5.57					
6	—	R_c	0.93	0.93	0.93					
7	Γ_{1a}	Γ_{1a}	4.83	4.83	4.83					
8	$\Gamma_{2a'}$	$\Gamma_{2a'}$	3.67	3.67	3.67					
9	R_a	R_{ac}	9.43	9.43	9.43					
10	—	$-X_{ac'}$	6.48	6.71	-4.21					
11	$X_{a'}$	$X_{a'}$	5.14	5.14	5.14					
12	—	$-X_c$	11.62	11.85	9.35					
13	Z_a	Z_{ac}	11.42	11.56	10.31					
14	θ_m	θ_m	42.0		42.0					
15	θ_a	$-\theta_{ac}$	34.5		24.1					
16	(14) - (15)	(14) + (15)	76.5		66.1					
17	$X_{m'} R_a$	$X_{m'} R_{ac}$		35.1						
18	$R_m X_{a'}$	$-R_m X_{ac'}$		27.8						
19	(17) - (18)	(17) + (18)		62.9						
20	$\sin(\theta_m - \theta_a)$	$\sin(\theta_m - \theta_{ac})$	0.972	0.977	0.915					
21	XK	XK	1.172	1.172	1.172					
22	$x1.88 p/f$	$x1.88 p/f$	0.1252	0.1252	0.1252					
23	$x\Gamma_{2m'}$	$x\Gamma_{2m'}$	2.67	2.67	2.67					
24	xI_m	xI_m	20.6	20.6	20.6					
25	xI_a	xI_{ac}	10.05	9.96	11.16					
26	$=T_s$	$=T_s$	78.7	78.5	82.5					
27	R_{ma}	R_{mac}	13.57	13.57	13.57					
28	X_{ma}	X_{mac}	2.76	2.99	0.49					
29	Z_{ma}	Z_{mac}	13.84	13.89	13.57					
30	$I_m Z_{ma} / Z_a$	$I_m Z_{mac} / Z_{ac}$	25.0	24.8	27.1					
31	CM/I_a	$E_c = I_{ac} X_c$	116.9	118.0	104.2					
32		$VA_c = I_{ac}^2 X_c$								
33		MFD	228	224	284					
34		T_s / I_L	3.15	3.16	3.04					

$\frac{1}{3}$ HP
115 VOLTS
60 CYCLES
4 POLES CALC. REF.
DATE 11-5-43

TYPE CAP START
SIGNATURE *E. S. Veinott*
L-

Figure 6. Form for calculating starting performance

items may be omitted; these items are 14 to 16, inclusive, or 17 to 19, inclusive, depending upon the preference of the calculator. Such a set of calculations is shown in column 1.

For calculating maximum-torque-per-ampere windings for capacitor-start motors, the following procedure has been found very useful and helpful. First, the known constants of the two windings are entered in lines 1, 2, 4, 7, 8, 11, 21, 22, 23. A value of R_c for line 6 is assumed and entered. The following lines are then computed in the order named: 3, 5, 9, 17, 27. Line 19 is then computed by making use of equation 118a. Then, the remaining items are computed and filled in in this order: 18, 10, 12, 13, 20, 24 to 33, inclusive. This procedure yields the microfarads for maximum starting torque per ampere, starting torque obtained, locked-rotor currents in each winding and in the line, and capacitor volts and volt-amperes. Whereas $X_{ac'}$ may be computed from equation 118 and the items

of Figure 6 calculated in consecutive order, the procedure outlined reduces considerably the numerical computations involved. Such a set of calculations is made in column 2. It is seen that the capacitor for column 1 was already chosen so as to give practically maximum starting torque per ampere. As a comparison, X_{ac} for maximum starting torque was computed, and complete calculations made as listed in column 3.

Maximum-torque-per-ampere windings for split-phase motors can be computed by a similar procedure, using equation 109a, but usually it is best to determine these windings from equations 110 and 111, or 110 and 115.

Symbols (See, Also, Table I)

- r_1 = primary resistance
- r_2 = secondary resistance, referred to primary
- C_r = $\frac{\text{apparent rotor resistance}}{\text{actual rotor resistance}}$ defined by equation 9
- C_R = $\frac{\text{apparent total reactance}}{\text{ideal total reactance}}$ defined by equation 10

X = ideal short-circuit reactance. This is the short-circuit reactance the motor would have if the secondary resistance were zero

X_0 = open-circuit reactance

T_s = starting torque, in ounce-feet

I_L = total locked-rotor current

P = number of poles

$K = \text{winding ratio} = \frac{\text{number of effective conductors in auxiliary winding}}{\text{number of effective conductors in main winding}}$

f = frequency in cycles per second

$$\dot{Z} = R + jX$$

$$Z = \sqrt{R^2 + X^2}$$

Appendix I

Locked-Rotor Impedance of Main Winding of a Single-Phase Induction Motor

In Figure 1 is shown the equivalent circuit of a single-phase induction motor under locked-rotor conditions. From inspection of this figure, the apparent impedance of the motor is

$$\dot{Z} = r_1 + jx_1 + \frac{(jx_m)(r_2 + jx_2)}{r_2 + j(x_m + x_2)} \quad (1)$$

which can be reduced, by ordinary algebraic processes, to the form

$$\dot{Z} = (r_1 + r_2 C_r) + (jX C_R) \quad (2)$$

where

$$C_r = \frac{x_m^2}{(x_2 + x_m)^2 + r_2^2} \quad (3)$$

$$C_R = \frac{1 + \left(\frac{x_1 + x_m}{X} \right) \left(\frac{r_2}{x_2 + x_m} \right)^2}{1 + \left(\frac{r_2}{x_2 + X_m} \right)^2} \quad (4)$$

X = "ideal short-circuit reactance"

$$= x_1 + \frac{x_2 x_m}{x_2 + x_m} \quad (5)$$

The equivalent circuit corresponding to equation 2 is given in Figure 1C. If the primary and secondary leakage reactances are equal

$$x_1 = x_2$$

Let

$$X_0 = x_1 + x_m = x_2 + x_m = \text{open-circuit reactance} \quad (6)$$

$$K_p = \frac{x_m}{x_m + x_1} = \frac{x_m}{x_m + x_2} = \sqrt{\frac{X_0 - X}{X_0}} \quad (7)$$

$$K_r = K_p^2 \quad (8)$$

When equations 6, 7, and 8 are used, equations 3 and 4 become

$$C_r = \frac{K_r}{1 + (r_2/X_0)^2} = \frac{\text{apparent rotor resistance}}{\text{actual rotor resistance}} \quad (9)$$

$$C_R = \frac{1 + \frac{r_2}{X} \frac{r_2}{X_0}}{1 + (r_2/X_0)^2} = \frac{\text{apparent total reactance}}{\text{ideal total reactance}} \quad (10)$$

Equations 9 and 10, when substituted into equation 2, give the identical results reported in equations 1, 2, and 3 of a previous paper,² wherein it was pointed out that the same equations were obtained by both the revolving-field and by the cross-field method of analysis.

Values of C_r and C_R have been plotted on Figure 2 to show the range of variation that may be expected in any given motor. These curves show that, for most practical purposes, C_r may be taken as equal to K_r , whereas C_R cannot be neglected, especially if the rotor resistance is even moderately high. Let

$$r_2' = r_2 C_r = \text{apparent secondary resistance} \quad (11)$$

$$X' = X C_R = \text{apparent total reactance} \quad (12)$$

Then equation 2 becomes

$$\dot{Z} = (r_1 + r_2') + jX'$$

It should be noted in passing that Figure 1B also applies to a polyphase induction motor; hence all equations in this appendix apply also to a polyphase induction motor.

Appendix II

Maximum Starting Torque Per Ampere for Split-Phase Motors

Consider point C in Figure 3, which defines the maximum starting torque per ampere. The first problem is to express the line amperes, I_L , in terms of constants already known

$$\overline{OC}^2 = \overline{OF}^2 - \overline{CF}^2 = \overline{OF}^2 - \overline{AF}^2 \quad (14)$$

(Line $\overline{OF}$ is omitted from Figure 3 to avoid confusion.)

But

$$\overline{OF}^2 = \overline{OA}^2 + \overline{AF}^2 + 2\overline{OA} \overline{AF} \sin \theta_m \quad (15)$$

Therefore

$$\begin{aligned} \overline{OC}^2 &= \overline{OA}^2 + 2\overline{OA} \overline{AF} \sin \theta_m \\ &= I_m^2 + \frac{2I_m E X_m'}{2X_a' Z_m'} \\ &= I_m^2 \left(1 + \frac{X_m'}{X_a'} \right) \end{aligned} \quad (16)$$

The line current is then

$$I_L = I_m \sqrt{\left(1 + \frac{X_m'}{X_a'} \right)} \quad (17)$$

Solving equation 17 for X_a' gives

$$X_a' = \frac{X_m'}{\left(\frac{I_L}{I_m} \right)^2 - 1} \quad (18)$$

But

$$I_L = I_m \sqrt{\frac{(R_m + R_a)^2 + (X_m' + X_a')^2}{(R_a^2 + X_a'^2)}} \quad (19)$$

[Refer to equation 125]

Eliminating I_L between equations 17 and 19 and solving for R_a gives

$$R_a = \frac{R_m X_a' + Z_m \sqrt{X_a' (X_m' + X_a')}}{X_m'} \quad (20)$$

$$\frac{R_a}{X_a'} = \frac{R_m}{X_m'} + \frac{Z_m}{X_m'} \sqrt{\frac{X_m' + X_a'}{X_a'}} \quad (21)$$

but, from equation 17

$$\sqrt{\frac{X_m' + X_a'}{X_a'}} = I_L / I_m \quad (22)$$

so, equation 21 becomes

$$\frac{R_a}{X_a'} = \frac{R_m + Z_m (I_L / I_m)}{X_m'} \quad (23)$$

or

$$R_a = \frac{X_a'}{X_m'} (R_m + Z_m I_L / I_m) \quad (24)$$

Substituting the value of X_a' in equation 18 for X_a' in equation 24 yields

$$R_a = \frac{R_m + Z_m (I_L / I_m)}{\left(\frac{I_L}{I_m} \right)^2 - 1} \quad (25)$$

Equations 25 and 18 define the resistance and reactance in the auxiliary-winding circuit, which yields a line current of I_L and a maximum-torque-per-ampere winding. These two equations completely define the auxiliary winding. If the reactance of the auxiliary winding is known, equation 20 defines the resistance required and equation 17 the resultant line current.

Appendix III

Starting-Torque Equations for a Capacitor-Start Motor

CONDITIONS FOR MAXIMUM STARTING TORQUE

Starting conditions for a capacitor-start motor are illustrated in Figure 4. Points C and D represent maximum starting torque per ampere, and maximum starting torque, respectively.

By the geometry of Figure 4

$$\widehat{AD} = \frac{180^\circ + 2\theta_m}{2} = 90^\circ + \theta_m$$

$$\widehat{DB} = 180^\circ - \widehat{AD} = 90^\circ - \theta_m \quad (26)$$

or

$$\theta_{ac} = \frac{90^\circ - \theta_m}{2}$$

$$\begin{aligned} \tan(-\theta_{ac}) &= \sqrt{\frac{1 - \cos(90^\circ - \theta_m)}{1 + \cos(90^\circ - \theta_m)}} \\ &= \sqrt{\frac{1 - \sin \theta_m}{1 + \sin \theta_m}} = \sqrt{\frac{Z_m - X_m'}{Z_m + X_m'}} \end{aligned}$$

or

$$\frac{-X_{ac}'}{R_{ac}} = \frac{Z_m - X_m'}{R_m} = \frac{R_m}{Z + X_m'}$$

or

$$-X_{ac}' = \frac{R_{ac}}{R_m} (Z_m - X_m') = \frac{R_{ac} R_m}{Z + X_m'} \quad (28)$$

Equation 28 expresses the total net reactance required in the auxiliary phase for maximum starting torque. This equation checks one given by Boothby,¹ if allowance is made for the difference in notation. The quantities given are all algebraic, not vector, quantities.

CONDITIONS FOR MAXIMUM STARTING TORQUE PER AMPERE

Maximum starting torque per ampere is represented by point C in Figure 4. The line current, OC , is expressed by the relationship

$$\overline{OC}^2 = \overline{OF}^2 - \overline{CF}^2 = \overline{OF}^2 - \overline{AF}^2 \quad (29)$$

but

$$\overline{OF}^2 = \overline{OA}^2 + \overline{AF}^2 + 2\overline{OA} \overline{AF} \cos \theta_m \quad (30)$$

therefore

$$\overline{OC}^2 = \overline{OA}^2 + 2\overline{OA} \overline{AF} \cos \theta_m \quad (31)$$

$$I_L^2 = I_m^2 + \frac{2I_m}{2} \frac{E}{R_{ac}} \times \frac{R_m}{Z_m} \quad (32)$$

$$I_L = I_m \sqrt{\frac{R_{ac} + R_m}{R_{ac}}} \quad (33)$$

or

$$R_{ac} = \frac{\widehat{R_m}}{(I_L / I_m)^2 - 1} \quad (34)$$

This gives an expression for the total resistance in the auxiliary phase. The next step is to find a similar expression for the total reactance in the auxiliary phase. The general expression for line current for a capacitor-start motor is

$$I_L = I_m \frac{\sqrt{(R_m + R_{ac})^2 + (X_m' + X_{ac}')^2}}{Z_{ac}} \quad (35)$$

(refer to equation 125)

Eliminating I_L by combining equations 33 and 35, and solving for X_{ac}' , one obtains

$$X_{ac}' = \frac{X_m' R_{ac} - Z_m \sqrt{R_{ac}(R_m + R_{ac})}}{R_m} \quad (36)$$

Remembering that

$$X_c = X_{ac}' - X_a' \quad (37)$$

equation 36 can be rewritten

$$X_c = \frac{X_m' R_{ac} - X_a' R_m - Z_m \sqrt{R_{ac}(R_m + R_{ac})}}{R_m} \quad (38)$$

Equation 38 gives the value of external capacitive reactance to be connected in series with the auxiliary winding to obtain maximum starting torque per ampere.

We still have to find X_{ac}' for maximum starting torque per ampere in terms of the line current. Dividing numerator and denominator of the right member of equation 36 by R_{ac}

$$X_{ac}' = \frac{X_m' - Z_m \sqrt{\frac{R_m + R_{ac}}{R_m}}}{R_m / R_{ac}} \quad (39)$$

By use of equation 33, equation 39 reduces to

$$\frac{X_m' - Z_m(I_L/I_m)}{\left(\frac{I_L}{I_m}\right)^2 - 1} \quad (40)$$

Equations 40 and 34 give the total reactance and total resistance required in the auxiliary phase for a maximum-torque-per-ampere winding having a locked-rotor current of I_L .

Appendix IV

Starting-Torque Equations for a Reactor-Start Motor

The starting conditions of a reactor-start motor are represented by Figure 5. Points C and D represent maximum starting torque per ampere and maximum starting torque, respectively.

MAXIMUM STARTING TORQUE

$$\widehat{AD} = \frac{180^\circ - 2\theta_a}{2} = 90^\circ - \theta_a \quad (41)$$

$$\theta_{mR} = \angle DAB = \frac{\widehat{BD}}{2} = \frac{90^\circ + \theta_a}{2} \quad (42)$$

By comparing equation 42 with the derivation of equation 28 in Appendix III, it is seen that

$$X_{mR} = \frac{R_a R_{mR}}{Z_a - X_a'} \quad \text{or} \quad \frac{R_{mR}}{R_a} (Z_a + X_a') \quad (43)$$

since

$$X_R = X_{mR} - X_m'$$

$$X_R = \frac{R_a R_{mR}}{Z_a - X_a'} - X_m' \quad \text{or} \quad \frac{R_{mR}}{R_a} (Z_a + X_a') - X_m' \quad (44)$$

Equation 44 gives the value of external reactance to be inserted in series with the main winding to obtain maximum starting torque.

MAXIMUM STARTING TORQUE PER AMPERE

In Figure 5, wherein point C represents maximum starting torque per ampere,

$$\overline{OC}^2 = \overline{OF}^2 - \overline{CF}^2 = \overline{OF}^2 - \overline{AF}^2 \quad (45)$$

but

$$\overline{OF}^2 = I_a^2 + \overline{AF}^2 + 2I_a \overline{AF} \cos \theta_a$$

or

$$\overline{OC}^2 = I_a^2 + \frac{2I_a E}{2R_{mR}} \times \frac{R_a}{Z_a} = I_L^2 \quad (46)$$

or

$$I_L = I_a \sqrt{\frac{R_{mR} + R_a}{R_{mR}}} \quad (47)$$

The line current, I_L , is also expressed by the relation

$$I_L = I_a \sqrt{\frac{(R_{mR} + R_a)^2 + (X_{mR} + X_a)^2}{Z_{mR}}} \quad (48)$$

[refer to equation 125]

Crossed-Coil Power-Factor Meters

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Synopsis: The fundamental relations governing operation of the crossed-coil type of power-factor meter are derived for the particular measurement applications on single-phase, three-wire two-phase, three-wire three-phase, and four-wire three-phase circuits. Emphasis is placed on the usefulness of a graph of either the equilibrium equation or the torque relation in determining the scale distribution.

DURING the past decade or so, the continued growth and, in recent years, the rapid expansion of distribution systems in industry has made industry more and more conscious of the importance of power factor. Although it is recognized that the electrical industry is gradually abandoning the concept of power factor as an indication of load conditions and is concentrating more on measurement of watts and vars, there still are many applications where the measurement of power factor is essential.

The increased demand for the measurement of power factor on single-phase and polyphase circuits has made it

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Equating the right-hand members of equations 47 and 48 and solving for X_{mR} yields

$$X_{mR} = \frac{X_a' R_{mR} + Z_a \sqrt{R_{mR}(R_a + R_{mR})}}{R_a} \quad (49)$$

The total external reactance to be connected in series with the main winding to obtain maximum starting torque per ampere is, therefore

$$X_R = \frac{X_a' R_{mR} + Z_a \sqrt{R_{mR}(R_a + R_{mR})}}{R_a} - X_m' \quad (50)$$

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2. SEGREGATION OF LOSSES IN SINGLE-PHASE INDUCTION MOTORS, C. G. Veinott. AIEE TRANSACTIONS, volume 54, 1935, pages 1302-6.
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necessary to design instruments with a large number of scale ranges. The range of the scale and the application of the instrument to a specified circuit determines the scale distribution. The factors which control scale distribution can be shown from the fundamental relations. To do this it will be necessary

1. To derive the basic torque and equilibrium equations for the single-phase, three-wire two-phase, three-wire three-phase, and four-wire three-phase power-factor meters.

2. To show how the scale distribution can be determined completely from a graph of either the equilibrium expression or the torque equations.

Examples will be made emphasizing the usefulness of these graphs for the selection of scale ranges for given scale angles of deflection.

It is realized that there are several ways by which power factor can be measured. The company with which the author is associated makes two types of power-factor meters. One uses a polarized Z-shaped vane which operates in a rotating magnetic field, and the other makes use of the principle of the crossed coil. In this article attention will be directed to the fundamentals of the crossed-coil-type power-factor meter.

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Figure 1. Type AD-6 power-factor meter

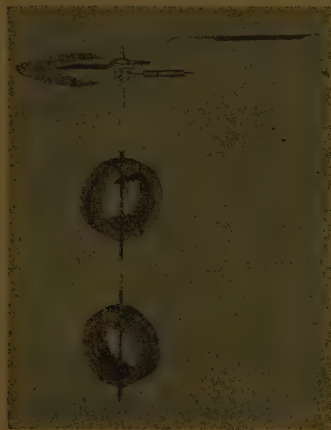


Figure 1a. Moving element of a power-factor meter, showing arrangement of crossed coils

Power-factor meters of the crossed-coil type similar to that shown in Figure 1 are adaptations of the original Tuma phase meter. (See page 546 of reference 1.) The Tuma phase meter as originally developed is a single-phase instrument for measuring the angle between two voltages or a voltage and a current. Although the three-wire three-phase application of the Tuma phase meter is more familiar because of use, it will be well to consider the single-phase application first because of its relative simplicity in analysis by comparison.

Single-Phase Power-Factor Meter: Scale Lag-Lead

The derivation of the fundamental relation is adequately covered in the

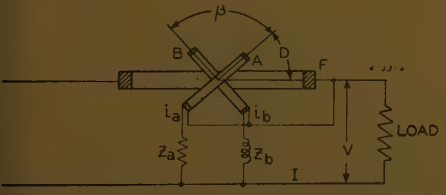


Figure 2. Diagram of a single-phase power-factor meter

literature for the single-phase meter. However, it will be advantageous to review this derivation in order to outline the method of attack that will be used in the analysis of the polyphase power-factor-meter applications. Figure 2 is a schematic diagram of the essential elements of a single-phase power-factor meter. Coils *A* and *B* compose the moving element. These coils are rigidly coupled to a shaft which is pivoted in an essentially uniform magnetic field produced by field coil *F*. An inductance in series with coil *B* and a resistance in series with coil *A* is connected to the external circuit as shown in the diagram. When current passes through coils *F*, *A*, and *B*, fields will be set up, and coils *A* and *B* will each experience turning moments in opposite directions. As *A* and *B* are rigidly connected, the moving element will turn to such a position that the resultant moment acting on it will be zero. The deflection *D* will then be an indication of the power-factor angle or phase angle between the load current and the line voltage.

Referring to Figure 2, let

- D* = Angle of deflection as measured between the planes of coils *F* and *A*
- β = Angle between coils *A* and *B*
- θ = Power-factor angle or angle between the load current *I* and the line voltage *V*
- Δ = Angle of lag between current in coil *B* and voltage *V*
- α = Angle of lag between the current in coil *A* and voltage *V*
- Z_a*, *Z_b* = Impedances of circuits *A* and *B* containing coils *A* and *B*, respectively
- i_a* = Instantaneous current in circuit *A*
- i_b* = Instantaneous current in circuit *B*
- i* = Instantaneous load current

There will be some mutual inductance between the moving and fixed coils, but in most applications the effect will be negligibly small. In the derivation of the fundamental relations the effect of mutual inductance will be neglected.

If voltage *V* is taken as the reference

vector from which phase differences are measured and the load current *I* is sinusoidal and is lagging, the instantaneous current values are

$$i = I \sin(\omega t - \theta)$$

$$i_a = \frac{V}{Z_a} \sin(\omega t - \alpha)$$

$$i_b = \frac{V}{Z_b} \sin(\omega t - \Delta)$$

The instantaneous torque acting on coil *A* will be

$$\tau_a = K_a i_a i \sin D$$

or

$$\tau_a = \frac{K_a I V}{Z_a} \sin D \sin(\omega t - \theta) \sin(\omega t - \alpha)$$

and the average torque over one complete period is

$$T_a = \left[\frac{K_a I V}{Z_a} \right] \sin D \frac{1}{T} \int_0^T \sin(\omega t - \theta) \times \sin(\omega t - \alpha) dt$$

where *T* is the period and is equal to the reciprocal of the frequency *f*. Frequency will be assumed constant in the derivation. *K_a* is a constant involving coil configuration, turns, and so forth.

If the preceding expression is integrated, the final average torque for coil *A* becomes

$$T_a = 1/2 \left[\frac{K_a I V}{Z_a} \right] \sin D \cos(\theta - \alpha) \quad (1)$$

Similarly, the instantaneous torque acting on coil *B* is

$$\tau_b = K_b i_b i \sin(D + \beta)$$

or

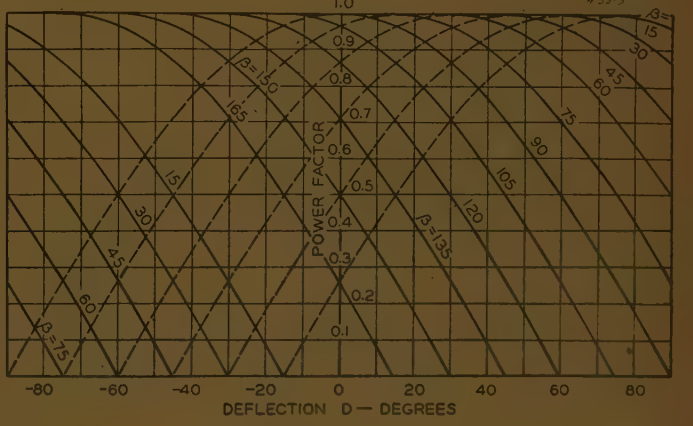
$$\tau_b = \left[\frac{K_b I V}{Z_b} \right] \sin(D + \beta) \sin(\omega t - \theta) \times \sin(\omega t - \Delta)$$

and the average torque over a period is

$$T_b = \left[\frac{K_b I V}{Z_b} \right] \sin(D + \beta) \frac{1}{T} \int_0^T \sin(\omega t - \theta) \times \sin(\omega t - \Delta) dt$$

Figure 3. Scale distribution curves of a single-phase power-factor meter for scale lag-lead, plotted from the equilibrium equation

- $\beta = \Delta$
- Curves of β for lagging power factor
- Curves of β for leading power factor



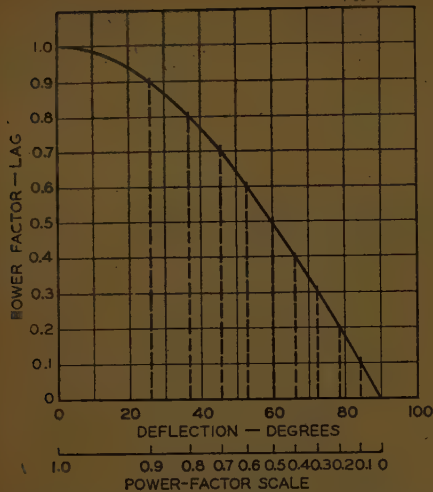


Figure 4. Scale distribution of a single-phase power-factor meter, for condition of $\beta = \Delta = 90$ degrees

Therefore

$$T_b = 1/2 \left[\frac{K_b I V}{Z_b} \right] \sin(D + \beta) \cos(\theta - \Delta) \quad (2)$$

Now for equilibrium the two torques must be equal

$$T_a = T_b \quad (3)$$

or

$$\begin{aligned} 1/2 \left[\frac{K_a I V}{Z_a} \right] \sin D \cos(\theta - \alpha) \\ = 1/2 \left[\frac{K_b I V}{Z_b} \right] \sin(D + \beta) \cos(\theta - \Delta) \quad (4) \end{aligned}$$

The foregoing is the general expression for equilibrium, and if the design of the instrument is such that

$$\frac{K_a}{Z_a} = \frac{K_b}{Z_b} \quad (5)$$

then equation 4 reduces to

$$\sin D \cos(\theta - \alpha) = \sin(D + \beta) \cos(\theta - \Delta) \quad (6)$$

In the ideal instrument $\alpha = 0$, $\beta = 90$ degrees and $\Delta = 90$ degrees. For these conditions equation 6 reduces to

$$\sin D \cos \theta = \sin(D + 90) \cos(\theta - 90)$$

or

$$\sin D \cos \theta = \cos D \sin \theta$$

and

$$\tan D = \tan \theta$$

from which

$$D = \theta \quad (9a)$$

In practice Δ is never exactly equal to 90 degrees, but Laws on page 548 of reference 1 has shown that the change in deflection from the unity-power-factor reference point is equal to the power-factor angle when $\beta = \Delta$.

If we had originally stated that the power factor was leading instead of lagging, equation 6 would have become

$$\sin D \cos(\theta - \alpha) = \sin(D + \beta) \cos(\theta + \Delta) \quad (9b)$$

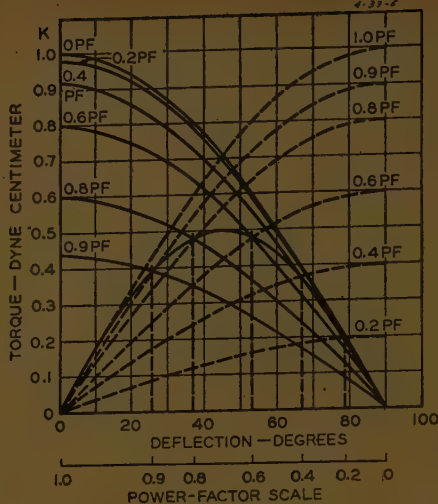


Figure 5. Scale distribution of a single-phase power-factor meter, plotted from the dynamic torque curves

$\beta = \Delta = 90$ degrees
--- Coil A
— Coil B

and for the ideal instrument the deflection

$$D = -\theta \quad (6c)$$

Thus we see that for lagging and leading power factors the power-factor angle is equal to plus and minus values of the deflection angle D , respectively.

Assuming in equation 6 that α is negligibly small and solving for D , we find that

$$\cot D = \frac{1}{\sin \beta (\cos \Delta + \tan \theta \sin \Delta)} - \cot \beta \quad (7)$$

Figure 3 is a plot of function 7 where β has been set equal to all assigned values of Δ . The full lines represent the curves of β for lagging power factor, whereas the dotted lines are the β curves for leading power factor.

If we arbitrarily let the deflection D be positive for lagging power-factor indications and let the instrument pointer be

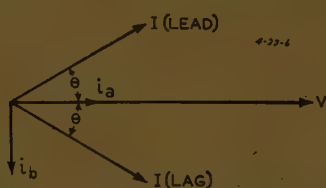


Figure 6. Vector diagram of a single-phase power-factor meter for scale lag-lead

aligned with the A coil, we are in a position to predict from these curves what will happen for any particular value of the angle β between the coils. For instance, if $\beta = 90$ degrees and it is desired to have a lag-lead scale with a total scale angle of 90 degrees, the power-factor scale would be approximately 0.7-1.0-0.7. This assumes that at unity power factor the

pointer indicates midscale and the deflection D must be ± 45 degrees.

Again suppose $\beta = 60$ degrees the scale angle is still 90 degrees and the pointer aligned with coil A . At unity power factor the pointer will indicate 30 degrees from mid scale on the lag side. Consequently, if it was desired to keep the mid-scale point the unity-power-factor point, it would be necessary to advance the pointer 30 degrees on the shaft. In the conventional design of instrument this may not be mechanically feasible, but if it were feasible, the scale distribution would be identical to that obtained for $\beta = 90$ degrees. From this family of curves it is evident that if the angle β between the coils is always adjusted so that it equals Δ , the power-factor scales will have identical distributions.

Figure 4 shows the normal distribution of an instrument for the condition where $\beta = \Delta = 90$ degrees. One obtains this distribution by projecting the power-factor points from the curve to the abscissa and labeling such points in terms of power factor instead of deflection. The resulting distribution constitutes the power-factor scale.

The scale distribution can also be determined completely from a plot of the dynamic torque curves of each moving coil. If the torque expressions 1 and 2

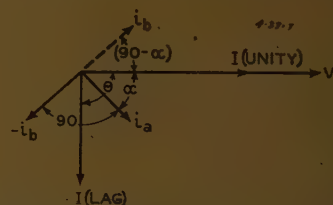


Figure 7. Vector diagram of a single-phase power-factor meter for scale all lag

for coils A and B are plotted, for values of power factor, the points of intersection of corresponding torque curves will form a locus of points of equilibrium. The points on this locus when projected to the abscissa will uniquely determine the scale distribution.

The dynamic torque curves are also valuable in that they describe how torque varies with angular deflection for each coil. Figure 5 shows a graph of these torque curves where for simplicity we have arbitrarily set

$$K = 1/2 \left[\frac{K_a I V}{Z_a} \right] = 1/2 \left[\frac{K_b I V}{Z_b} \right] \quad (8)$$

Theoretically it is possible to obtain a scale of 0-1.0-0 power factor, but this would require an instrument scale angle of 180 degrees. In the types AD-6 and 7 power-factor meters, the maximum

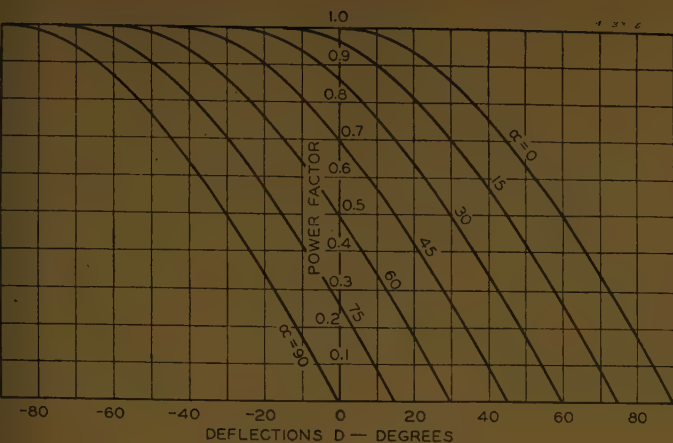


Figure 8. Scale distribution curves of a single-phase power-factor meter for scale all lag, plotted from the equilibrium equation
 $\beta = 90$ degrees

scale for lag and lead is 0.5-1.0-0.5 power factor. This is obtained with $\beta = \Delta = 90$ degrees and the pointer aligned with coil A.

Occasionally it is required to produce a scale all lag or all lead. In the foregoing analysis we have seen that theoretically it is possible to obtain a scale all lag or all lead by mechanically shifting the pointer with respect to coils A and B. Mechanical design may make it virtually impossible to obtain the proper pointer-coil relation to give a scale all lag or lead. Consequently, it becomes necessary to make certain changes in the electrical constants. The method for doing this is discussed in the following section.

Single-Phase Power-Factor Meter: Scale All Lag

In the following analysis let us assume a condition in which the scale is all lag, that is, unity power factor is at the right end of the scale and zero power factor at the left end. This analysis can also apply to any such scale range as 0.3 to 0.8 power-factor lag. To do this and still keep the same mechanical arrangement of coils and pointer as in the previous section it is necessary to shift electrically the 90-degree relation of the potential circuits such that the instrument indication will fall within the prescribed scale angle.

In the standard lag-lead instrument of the previous section the current i_a in circuit A is in phase with the applied voltage and i_b is 90 degrees lagging this voltage. Vectorially, the voltage V and i_a bisect the angle of the lead and lag load-current vectors which represent the extremes of the power-factor scale range. Figure 6 shows this vector relation. If the scale is to be all lag, then the current i_a must be made to lag V by some angle α such that the current vector i_a will approximately bisect the angle enclosed by the load-current vectors repre-

senting the ends of the power-factor scale. Current i_b must also lag V by $(\alpha + 90)$. To obtain the proper lag relation between i_b and V capacitance and resistance are placed in series with coil B. Current i_a will now lead V by $(90 - \alpha)$ but can be made to lag by reversing the connections. Figure 7 shows the new vector relations. By referring to the vector diagram in Figure 7 the instantaneous current values can now be determined and the torque expressions derived. The instantaneous currents are

$$i = I \sin(\omega t - \theta)$$

$$i_a = \frac{V}{\sqrt{R_a^2 + L_a^2 \omega^2}} \sin(\omega t - \alpha)$$

$$i_b = \frac{V}{\sqrt{R_b^2 + 1/C_b^2 \omega^2}} \sin[\omega t + (90 - \alpha)]$$

Following the previous procedure the torque on coil A is

$$T_a = \left[\frac{K_a I V}{\sqrt{R_a^2 + L_a^2 \omega^2}} \right] \sin D \frac{1}{T} \times \int_0^T \sin(\omega t - \theta) \sin(\omega t - \alpha) dt$$

which upon integration yields

$$T_a = 1/2 \left[\frac{K_a I V}{\sqrt{R_a^2 + L_a^2 \omega^2}} \right] \times \sin D \cos(\theta - \alpha) \quad (9)$$

and the torque on coil B is

$$T_b = \left[\frac{K_b I V}{\sqrt{R_b^2 + 1/C_b^2 \omega^2}} \right] \sin(D + \beta) \frac{1}{T} \times \int_0^T \sin(\omega t - \theta) \sin[\omega t + (90 - \alpha)] dt$$

$$\text{or}$$

$$T_b = 1/2 \left[\frac{K_b I V}{\sqrt{R_b^2 + 1/C_b^2 \omega^2}} \right] \times \sin(D + \beta) \sin(\theta - \alpha) \quad (10)$$

For equilibrium

$$T_a = T_b$$

When

$$\frac{K_a}{\sqrt{R_a^2 + L_a^2 \omega^2}} = \frac{K_b}{\sqrt{R_b^2 + 1/C_b^2 \omega^2}}$$

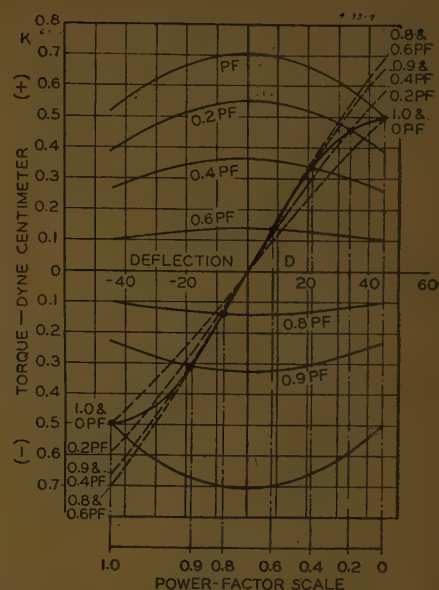


Figure 9. Scale distribution of a single-phase power-factor meter with scale all lag, determined from the dynamic torque curves

$\alpha = 45$ degrees
 $\beta = 90$ degrees
--- Coil A
— Coil B

the equilibrium equation becomes

$$\sin D \cos(\theta - \alpha) = \sin(D + \beta) \sin(\theta - \alpha) \quad (11)$$

For the case when $\beta = 90$, expression 11 becomes

$$\sin D \cos(\theta - \alpha) = \cos D \sin(\theta - \alpha)$$

or

$$\tan D = \tan(\theta - \alpha)$$

from whence

$$D = \theta - \alpha \quad (11a)$$

The deflection is now equal to the difference between θ and α and not equal to θ

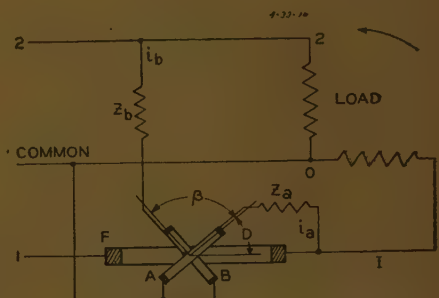


Figure 10. Diagram of a three-wire two-phase power-factor meter

as previously. However α is a constant, and the deflection D is proportional to θ . If equation 11 is solved for D

$$\cot D = \frac{\cot(\theta - \alpha)}{\sin \beta} - \cot \beta \quad (12)$$

The plot of this expression for $\beta = 90$

degrees and varying α is shown on Figure 8. It will be noticed that the scale distribution for any one value of α is the same distribution as developed in Figure 4 for the single-phase power-factor meter

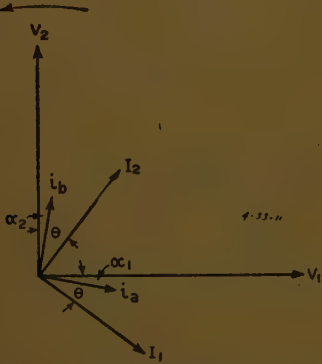


Figure 11. Vector diagram of a three-wire two-phase power-factor meter

with scale lag-lead. In fact, expression 12 for $\alpha=0$ and $\beta=90$ reduces to expression 7 for $\beta=\Delta=90$. From this we could have predicted the distribution would be the same.

The torque curves of each element depicted in Figure 9 are radically different from those in Figure 4, but the resultant scale distribution is the same. Although angle α was arbitrarily set equal to 45 degrees for these torque curves, other values of α would give similar scale distributions. The essential difference for other values of α would be revealed in different values of the angle of deflection.

By referring again to Figure 8 it will be noted that if it is required to have a scale 0.3 to 0.8 power factor or the current lags the voltage by 72.5 and 37 degrees, respectively, α should be chosen to be approximately 60 degrees. As pointed out previously, it is necessary to choose α intermediate between the angles representing the scale ends if the same coil and pointer relation is to be maintained, namely, the pointer lines up with the A

coil. If this is done, then the resulting scale angle will be approximately 38 degrees.

Three-Wire Two-Phase Power-Factor Meter

Some applications require the measurement of power factor on three-wire two-phase circuits.

In Figure 10 coils A and B are connected in series with resistors to phases 1 and 2, respectively, while their common lead is connected to the neutral. The same notation shall be used as previously with the exception that α_1 and α_2 are the angles of lag between the currents in circuits A and B and the load voltage. These lagging currents are due to the inductive effect of the movable coils.

With reference to Figure 11 which is the vector diagram for a balanced inductive load the instantaneous current values for lagging power factor are

$$i = I \sin(\omega t - \theta)$$

$$i_a = \frac{V}{Z_a} \sin(\omega t - \alpha_1)$$

$$i_b = \frac{V}{Z_b} \sin(\omega t + [90 - \alpha_2])$$

The coil torques are now

$$T_a = \left[\frac{K_a IV}{Z_a} \right] \sin D \frac{1}{T} \int_0^T \sin(\omega t - \theta) \times \sin(\omega t - \alpha_1) dt$$

$$T_a = 1/2 \left[\frac{K_a IV}{Z_a} \right] \sin D \cos(\theta - \alpha_1) \quad (13)$$

$$T_b = \left[\frac{K_b IV}{Z_b} \right] \sin(D + \beta) \frac{1}{T} \times \int_0^T \sin(\omega t - \theta) \sin[\omega t + (90 - \alpha_2)] dt$$

$$T_b = 1/2 \left[\frac{K_b IV}{Z_b} \right] \sin(D + \beta) \sin(\theta - \alpha_2) \quad (14)$$

For equilibrium T_a must equal T_b ; therefore

$$1/2 \left[\frac{K_a IV}{Z_a} \right] \sin D \cos(\theta - \alpha_1) = 1/2 \left[\frac{K_b IV}{Z_b} \right] \sin(D + \beta) \sin(\theta - \alpha_2) \quad (15)$$

Letting

$$K_1 = \frac{K_a}{Z_a} \text{ and } K_2 = \frac{K_b}{Z_b}$$

and solving for D results in

$$\cot D = \frac{K_1}{K_2} \left[\frac{1 + \tan \theta \tan \alpha_1}{\sin \beta \left(\tan \theta \frac{\cos \alpha_2}{\cos \alpha_1} - \frac{\sin \alpha_2}{\cos \alpha_1} \right)} \right] - \cot \beta \quad (16)$$

If design is such that $K_1=K_2$ then $\alpha_1=\alpha_2=\alpha$ and equation 16 reduces to

$$\cot D = \frac{\cot(\theta - \alpha)}{\sin \beta} - \cot \beta \quad (17)$$

This relation is identical to equation 12 for the single-phase power-factor meter

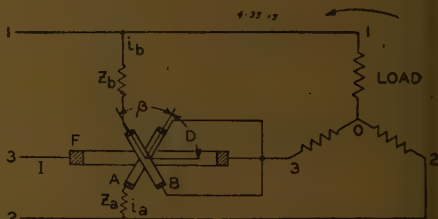


Figure 13. Diagram of a three-wire three-phase power-factor meter

with scale all lag. However, in general α in equation 17 is small and can be neglected. If this is done, the deflection then reduces to

$$\cot D = \frac{\cot \theta}{\sin \beta} - \cot \beta \quad (18)$$

The graph of this expression will give the same scale distribution as the single-phase power-factor meter for $\beta=90$ degrees. Equation 7 is identical to equation 18 for $\Delta=90$ degrees. The essential difference between the operation of a power-factor meter on three-wire two-phase and a single-phase meter with scale lag-lead is that in the three-wire two-phase application the 90-degree relation is obtained by the 90-degree displacement between phase voltages, whereas in the single-phase meter it is necessary to lag the current in one circuit by the use of a series reactor.

If expression 18 is plotted for lag and lead power factors with varying β , a family of distribution curves will result as shown on Figure 12. Each value of β

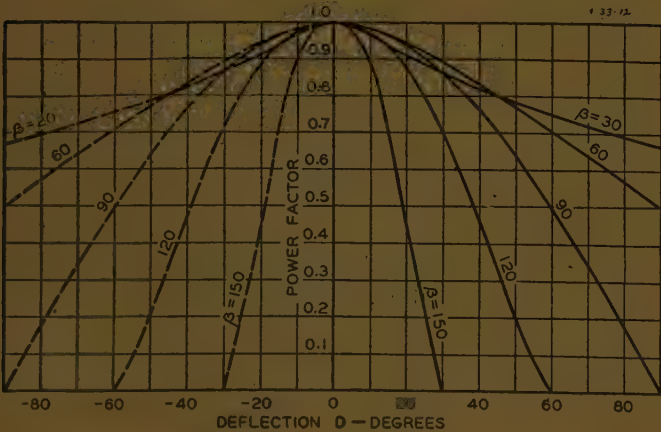


Figure 12. Scale distribution curves for a three-wire two-phase power-factor meter, plotted from the equilibrium equation
— β curves for lagging power factor
--- β curves for leading power factor

will give a different scale distribution. The curve that will give the same scale distribution as the single-phase application is the one for which $\beta = 90$ degrees.

It can be seen from Figure 12 that for a given scale angle of 90 degrees with, for example, $\beta = 60$ degrees that the maximum power-factor scale that can be obtained for a scale all lag or all lead would be 0.5 to 1.0 power factor. Also, for a

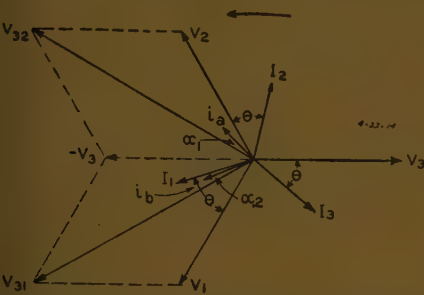


Figure 14. Vector diagram of a three-wire three-phase power-factor meter

scale having both lag and lead with the same scale angle, the maximum range would be approximately 0.8 lag to 0.8 lead.

It will not be necessary to plot the dynamic torque curves as the curves of Figure 5 with the resulting scale distribution apply to the three-wire two-phase power-factor meter for $\beta = 90$ degrees.

Three-Wire Three-Phase Power-Factor Meter

Figure 13 shows the connection of a power-factor meter on a three-wire three-phase balanced inductive load. Again use is made of the phase relation between voltages to obtain the desired condition for power-factor measurement. The only mechanical difference between the three-wire two-phase and three-wire three-phase power-factor meter is the setting of the coil angle β and pointer location. Although the mechanical difference is slight, the torque and distribution characteristics are radically different between the two instruments.

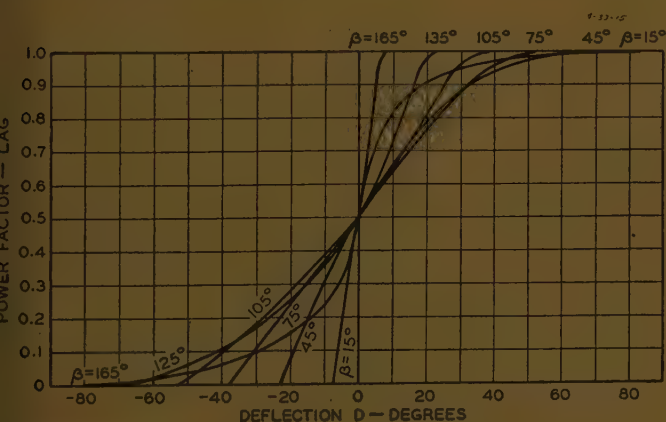


Figure 15. Scale distribution curves for a three-wire three-phase power-factor meter, plotted from the equilibrium equation

$\alpha = 0$

In reference to the vector diagram in Figure 14 the instantaneous current values are

$$i_a = I_a \sin(\omega t - \theta) = I \sin(\omega t - \theta)$$

for balanced currents

$$i_a = \frac{V_{23}}{Z_a} \sin[\omega t + (150 - \alpha_1)]$$

$$i_b = \frac{V_{31}}{Z_b} \sin[\omega t - (150 + \alpha_2)]$$

where α_1 = lag angle between i_a and V_{23} and α_2 = lag angle between i_b and V_{31} . It will be noted that for stability of instrument operation it is necessary to reverse line voltage V_{13} .

For balanced inductive loads the coil average torques are

$$T_a = 1/4 \left[\frac{K_a I V}{Z_a} \right] \sin D [-\sin(\theta - \alpha_1) - \sqrt{3} \cos(\theta - \alpha_1)] \quad (19)$$

$$T_b = 1/4 \left[\frac{K_b I V}{Z_b} \right] \sin(D + \beta) [\sin(\theta - \alpha_2) - \sqrt{3} \cos(\theta - \alpha_2)] \quad (20)$$

For equilibrium $T_a = T_b$. Setting $T_a = T_b$ and solving for the deflection D , we have

$$\cot D = \frac{K_1}{K_2} \left[\frac{1 - \tan \theta \cot \alpha_1 - \sqrt{3} \tan \theta - \sqrt{3} \cot \alpha_1}{\sin \beta \left(\tan \theta \frac{\cos \alpha_2}{\sin \alpha_1} - \frac{\sin \alpha_2}{\sin \alpha_1} - \sqrt{3} \frac{\cos \alpha_2}{\sin \alpha_1} - \sqrt{3} \tan \theta \frac{\sin \alpha_2}{\sin \alpha_1} \right)} \right] - \cot \beta \quad (21)$$

where

$$K_1 = \frac{K_a}{Z_a}, \text{ and } K_2 = \frac{K_b}{Z_b}$$

If design is such that

$$K_1 = K_2$$

then

$$\alpha_1 = \alpha_2 = \alpha$$

and equation 21 reduces to

$$\cot D = \frac{\tan \alpha (1 - \sqrt{3} \tan \theta) - (\tan \theta + \sqrt{3})}{\sin \beta [(\tan \theta - \sqrt{3}) - \tan \alpha (1 + \sqrt{3} \tan \theta)] \cot \beta} \quad (22)$$

In most cases α is small, and

$$\cot D = - \left[\frac{\tan \theta + \sqrt{3}}{\sin \beta (\tan \theta - \sqrt{3})} + \cot \beta \right] \quad (23)$$

When the power factor becomes zero, equation 23 is indeterminate but can be evaluated. For power factor = 0

$$\cot D = - \left[\frac{1 + \cos \beta}{\sin \beta} \right] \quad (24)$$

The family of curves resulting from equation 23 are shown in Figure 15. Each curve will give one particular scale distribution. For any given scale angle one can determine from these curves the power-factor scale range for any coil angle β .

Expression 23 was derived for the condition of lagging power factor. For leading power factor the relation for the deflection becomes

$$\cot D = \frac{\tan \theta - \sqrt{3}}{\sin \beta (\tan \theta + \sqrt{3})} + \cot \beta \quad (23a)$$

This expression when plotted will give the same scale distribution as equation 23, but the angles of deflection D will have different values. However, for an instrument whose pointer is set to bisect the angle β between coils, the scale distribution will be symmetrical about the unity-power-factor point for lag and lead conditions with any given value of β .

The value of β most commonly used is the one for which $\beta = 75$ degrees. This angle is selected because the resulting scale distribution more nearly approaches linearity than any other value of β .

If the curve for $\beta = 75$ degrees is separately plotted as on Figure 16, the scale distribution is more clearly determined. It will be noted from this distribution that if the scale is to be lag-lead for a scale angle of 90 degrees, the maximum power-

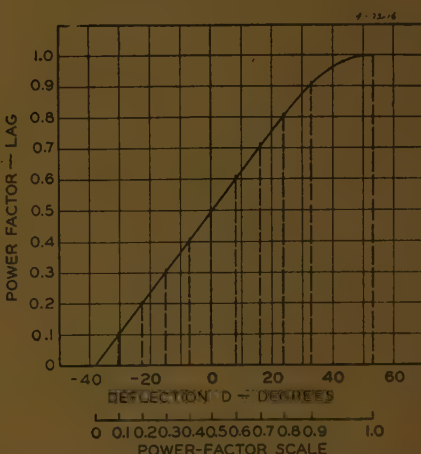


Figure 16. Scale distribution of a three-wire three-phase power-factor meter for $\beta = 75$ degrees

$\alpha = 0$

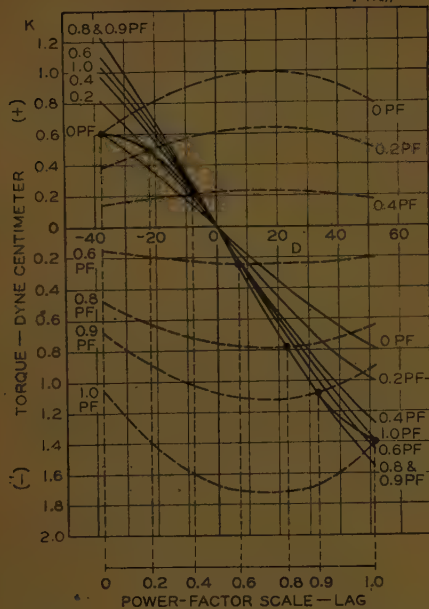


Figure 17. Scale distribution of a three-wire three-phase power-factor meter, plotted from the dynamic torque curves

$\alpha=0$ — Coil A
 $\beta=75$ degrees --- Coil B

factor range will be approximately 0.6 lag to 0.6 lead.

Figure 17 is a plot of the dynamic torque curves which also show the resulting scale distribution. Barring inaccuracies in graphing, the distribution in Figure 17 and Figure 16 are identical.

Four-Wire Three-Phase Power-Factor Meter

The last application that shall be discussed in this article is the condition for four-wire three-phase power-factor meas-

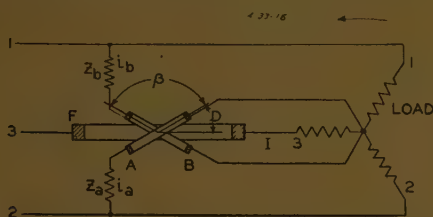


Figure 18. Diagram of a four-wire three-phase power-factor meter

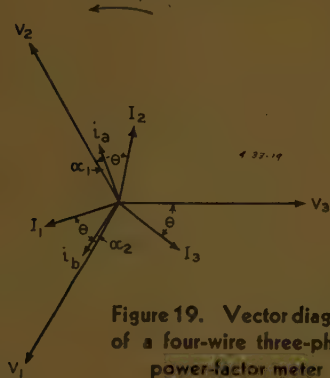
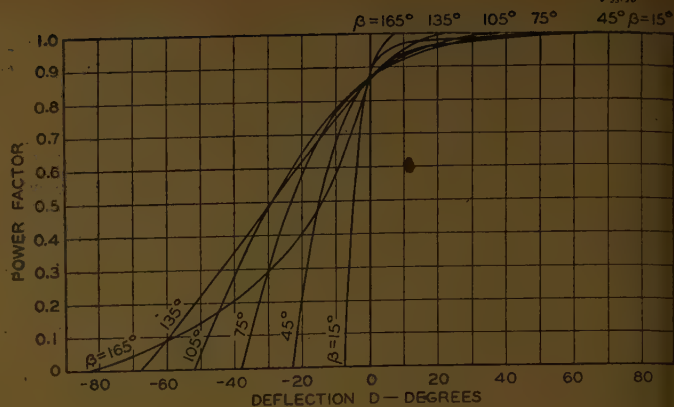


Figure 19. Vector diagram of a four-wire three-phase power-factor meter

Figure 20. Scale distribution curves of a four-wire three-phase power-factor meter, plotted from the equilibrium equation
 $\alpha=0$



urement. In this case phase-to-neutral voltages are used instead of phase-to-phase voltages as in the three-wire three-phase application. Angle β is then selected to give the best scale distribution for the particular scale desired.

With reference to Figure 19, which is the vector diagram of the instrument connections schematically shown in Figure 18, the instantaneous currents for a balanced inductive load using V_a as the reference vector are

$$i_a = I_3 \sin(\omega t - \theta) = I \sin(\omega t - \theta)$$

$$i_a = \frac{V_1}{Z_a} \sin(\omega t + 120 - \alpha_1)$$

$$i_b = \frac{V_1}{Z_b} \sin(\omega t - 120 - \alpha_2)$$

The average coil torques turn out to be

$$T_a = 1/4 \left[\frac{K_a I V}{Z_a} \right] \sin D [-\sqrt{3} \times \sin(\theta - \alpha_1) - \cos(\theta - \alpha_1)] \quad (25)$$

and

$$T_b = 1/4 \left[\frac{K_b I V}{Z_b} \right] \sin(D + \beta) [\sqrt{3} \times \sin(\theta - \alpha_2) - \cos(\theta - \alpha_2)] \quad (26)$$

For

$$K_1 = \frac{K_a}{Z_a} \text{ and } K_2 = \frac{K_b}{Z_b}$$

the expression for the deflection at equilibrium is

$$\cot D = \frac{\sqrt{3} - \sqrt{3} \tan \theta \cot \alpha_1 - \tan \theta - \cot \alpha_1}{\frac{K_1}{K_2} \sin \beta \left(\sqrt{3} \tan \theta \frac{\cos \alpha_2}{\sin \alpha_1} - \sqrt{3} \frac{\sin \alpha_2}{\sin \alpha_1} - \frac{\cos \alpha_2}{\sin \alpha_1} - \tan \theta \frac{\sin \alpha_2}{\sin \alpha_1} \right) - \cot \beta} \quad (27)$$

When the design is such that

$$K_1 = K_2, \text{ and } \alpha_1 = \alpha_2 = \alpha$$

then equation 27 reduces to

$$\cot D =$$

$$\frac{\tan \alpha (\sqrt{3} - \tan \theta) - (\sqrt{3} \tan \theta + 1)}{\sin \beta [(\sqrt{3} \tan \theta - 1) - \tan \alpha (\sqrt{3} + \tan \theta)] - \cot \beta} \quad (28)$$

For $\alpha=0$, which is a practical assumption

$$\cot D = - \left[\frac{\sqrt{3} \tan \theta + 1}{\sin \beta (\sqrt{3} \tan \theta - 1)} + \cot \beta \right] \quad (29)$$

By direct comparison of equation 29 with 23 the similarity that exists will be observed. The only difference is in the location of the $\sqrt{3}$ term. This slight difference, however, makes quite a difference in the scale distribution and torque curves. For the condition where the power factor is zero the evaluated indeterminate form of equation 29 reduces to the same expression as equation 24.

The analysis of the four-wire three-phase application is quite similar to the three-wire three-phase case. For this reason details have been omitted. Expression 29 has been derived for the condition of lagging power factor, but a similar expression for leading power factor would give the same scale distribution.

From Figure 20 one can see that it is possible for a 100-degree scale to obtain a scale range of 0.9-1.0-0.9 power factor if β is set equal to approximately 75 degrees. The most common condition in practice for a lag-lead scale is for β to equal 105 degrees. The scale distribution for this condition is shown in Figure 21. Figure 22 also gives the same distribution as plotted from the dynamic torque curves.

The foregoing analyses show the theoretical possibilities of scale ranges in power-factor meters of the crossed-coil type. A variety of scale distributions is inherent and to a large extent dependent on the particular circuit application of the instrument. Limitations on range and distribution are necessarily imposed

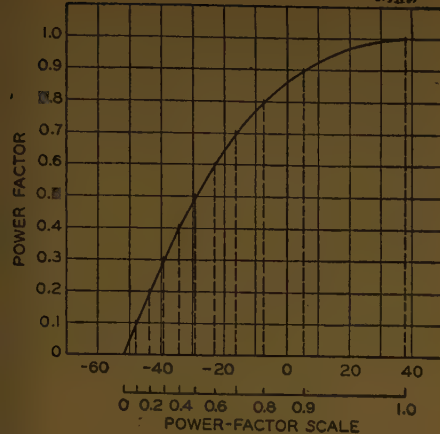


Figure 21. Scale distribution of a four-wire three-phase power-factor meter for $\beta=105$ degrees

$$\alpha=0$$

because of mechanical design; however, the derived distribution curves for each application should prove of value as an aid in selecting proper power-factor scale ranges for given scale angles of deflection.

Power Factor of Unbalanced Polyphase Circuits

In the previous summary of polyphase power-factor meters, emphasis was placed on the application to systems having symmetrical sets of voltages and currents or balanced loads. Although it is beyond the scope of this article to analyze mathematically the effect of system unbalance on the measurement of power factor on polyphase circuits, it might be well to consider briefly this question. It is conceivable that, for a given condition of unbalance, the torque equations of a polyphase power-factor meter could be derived, and an expression for the instrument indication obtained. This indication may or may not be an indication of the power factor of the system. The question immediately raised is: "What is the meaning of power factor in a polyphase circuit?" In the past there has been some disagreement as to what power factor is in a polyphase circuit and only recently has any definition been recorded. "The American Standard Definition of Electrical Terms" gives several definitions of power factor. To quote from this publication, they are

"Power factor is the ratio of active power to apparent power. The power factor Δ is given by the equation

$$\Delta = P/U$$

[where P =active power and U =apparent power]. It follows that the power factor of a polyphase circuit must be designated as arithmetic or algebraic to indicate whether arithmetic or algebraic apparent power is

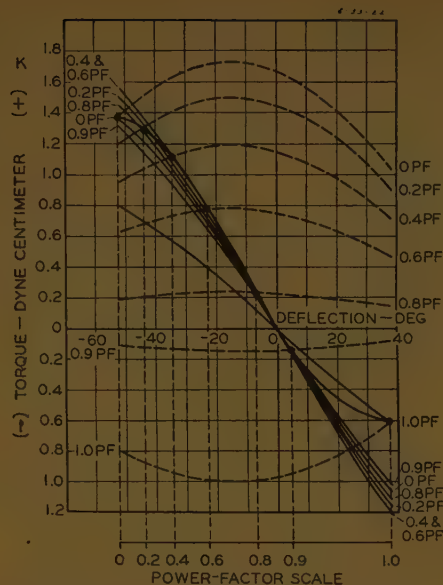


Figure 22. Scale distribution of a four-wire three-phase power-factor meter, plotted from the dynamic torque curves

$$\alpha=0$$

$$\beta=105 \text{ degrees}$$

— Coil A
--- Coil B

used in the denominator. If both the currents and potential differences are sinusoidal and if both form symmetrical sets, then

$$\Delta = \cos(\beta - \alpha)$$

"Vector power factor is the ratio of the active power to the vector power... If both the currents and potential differences are sinusoidal and if both form symmetrical

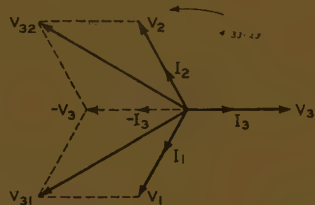


Figure 23. Vector diagram of a three-wire three-phase balanced resistance load $I_1=I_2=I_3=I$

sets, then the vector power factor is the same as the power factor."

These definitions clearly suggest that three different power factors can be realized which are determined by the use of arithmetic or algebraic apparent power or vector power. For balanced systems the three power factors are equal for all angular displacements between phase voltages and currents. In the unbalanced system the three power factors are equal only when all phase currents are inphase with their respective phase voltages and are different for other angular displacements. Unity power factor is a term that is commonly used to denote the condition when a current and a voltage are inphase.

For an example of the effect of un-

balance on instrument indication let us take a simple extreme case. Suppose that the three-wire three-phase instrument shown in Figure 13 is connected to a balanced pure resistance load. As unity power factor, previously defined, exists in this system, let us further assume that the instrument is calibrated to indicate this unity power factor. Now let us unbalance the load by opening the connection to the load at two, thereby making the current in this phase equal to zero. Also let the three line voltages remain a symmetrical set and the instrument potential circuits be excited. For this extreme condition of unbalance the current vector I , which originally was inphase with phase voltage V_3 , will now have shifted 30 degrees leading V_3 since it will be inphase with line voltage V_{31} . Although unity power factor still exists for the unbalanced condition, the instrument no longer indicates unity power factor but is in error by 30 electrical degrees. Vector diagrams shown in Figures 23 and 24 will serve to clarify these two conditions.

One can see that it is possible to have several combinations of system unbalance that might conceivably produce the same instrument indication. If this is true, then any given instrument indication would tell the observer nothing concerning the condition of circuit unbalance that produced that indication. Con-

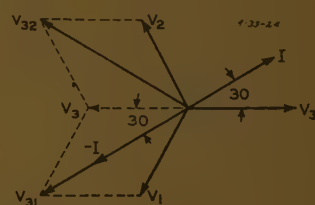


Figure 24. Vector diagram of a three-wire three-phase resistance load-balanced voltages $I_2=0, I_1=I_3=I$

versely, as previously pointed out, for a given unbalance an instrument indication might be obtained by means of a mathematical derivation that would tie up the indication with a particular unbalance condition, but what would be the practical value of this since the condition of system unbalance is already known?

For the standard adopted application of power-factor indicators on polyphase circuits it is reasonable to assert that, unless the polyphase system is balanced, the power-factor-meter indication is without significance.

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Crossbar Toll Switching System

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F. F. SHIPLEY
MEMBER AIEE

IN AUGUST of 1943 a new mechanical toll switching system was placed in service in Philadelphia. It was designed by engineers of the Bell Telephone Laboratories and of the department of operation and engineering of the American Telephone and Telegraph Company for large toll centers, particularly those where most of the offices are of the panel and crossbar types. The Philadelphia installation was planned before the war. Even then it was apparent that a mechanical switching system was needed urgently to secure faster and more economical switching. War conditions produced an abnormal growth in toll traffic that accentuated the need for the new equipment. The system was therefore installed as rapidly as the heavy load of war work on the engineering and manufacturing organizations of the Bell System would permit. It is now contributing materially to the war effort by providing adequate switching facilities for the increased volume of traffic.

This new toll switching system includes the following important features:

1. Crossbar switching equipment with senders and markers.
2. Operator dialing or pulsing over toll lines to panel and crossbar areas.
3. A cordless switchboard for handling traffic which cannot be dialed or pulsed through the system by distant operators.
4. A new rapid method of transmitting switching codes known as a-c key pulsing.
5. Four-wire switching, that is, the provision of separate conductors for voice transmission in each direction.

The function of toll switching equipment is to provide connections that will enable subscribers to converse with other subscribers in localities too distant to be reached over their own local network. If the toll areas in which the calling and called subscribers are located have a sufficient community of interest, there may be direct circuits between them, and at each terminal there will be a switched connection to a local office. Where the

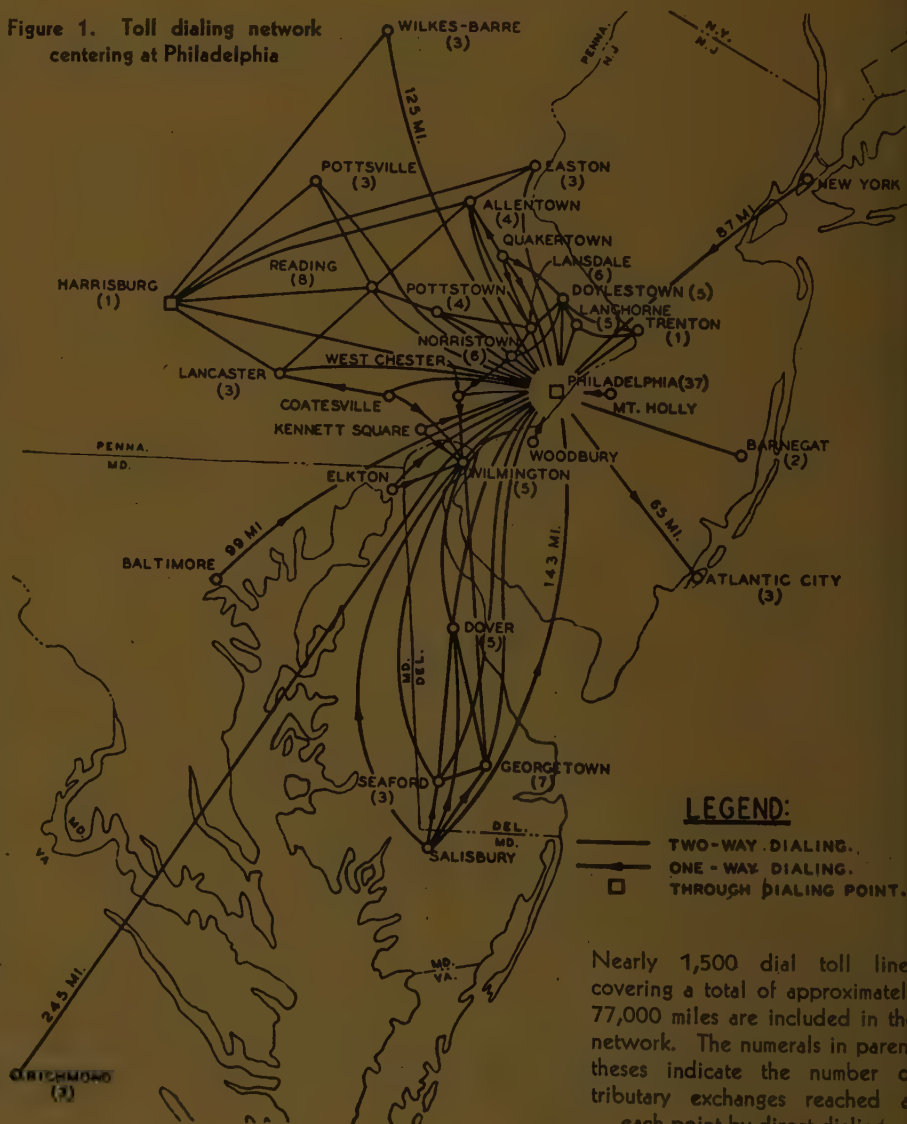
call involves two toll offices having no direct circuits between them, it must be routed through one or more intermediate toll offices, and switching connections will be required at each intermediate point as well as at the originating and terminating offices.

In the past it has been the ordinary practice to have every connection made by an operator who inserts plugs on the two ends of a cord into jacks on which the toll lines and trunks are terminated. In recent years an improved practice, known as toll-line dialing, has been applied in a few of the smaller toll areas where step-by-step switching equipment is used in the local offices. With this method, the outward toll operator who accepts the subscriber's call plugs into a

toll line, and then by means of a dial temporarily associated with her cord sends dial pulses to direct the movement of switches in the distant toll office to select a trunk to the called subscriber's local office. She continues by dialing the subscriber's listed number to drive switches in the local office to establish a connection. The subscriber's bell is then rung automatically by the local circuit. If intermediate switching is involved, the operator also dials the connection through the intermediate office. Thus the manual labor of establishing connections at intermediate and inward toll switchboards is eliminated, the outward operator's work-time is reduced since she does not have to pass orders for connections and wait for them to be established, and the subscriber receives faster service.

In the toll dialing operation just described, the switching equipment in toll and local offices is all of the step-by-step variety, the movement of switches being under control of impulses dialed on a decimal basis. In areas where the local

Figure 1. Toll dialing network centering at Philadelphia



Paper 44-42, recommended by the AIEE committee on communication for presentation at the AIEE winter technical meeting, New York, N. Y., January 24-28, 1944. Manuscript submitted November 10, 1943; made available for printing December 11, 1943.

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Nearly 1,500 dial toll lines covering a total of approximately 77,000 miles are included in the network. The numerals in parentheses indicate the number of tributary exchanges reached at each point by direct dialing.

Now assume an outward call to a Chicago subscriber. The Philadelphia-Chicago group operates on a ring-down basis, and the outward operator, after selecting the tandem trunk, will dial or key only the three-digit code representing the Chicago group. The crossbar equipment will make the connection to an idle Chicago toll line and cause ringing current to be sent over the line. This will light a lamp associated with the toll line in Chicago, where an operator will answer the call. The outward operator in Philadelphia, will pass the order to the Chicago operator, who will complete the call. The outward operator must remain on the connection until the called subscriber answers, in order to start timing, because supervisory signals to indicate the called subscriber's answer and hang-up are not returned over a ringdown line. At the end of conversation she will pull down her cords when the calling subscriber hangs up. This will release the connection through the switches to the Chicago toll line. The inward operator at Chicago

[illegible]

TRANSACTIONS 303

will release her connection upon receipt of a lighted cord lamp indicating that the called subscriber has hung up.

INWARD CALLS

An inward call over a dial toll line, illustrated by Figure 5, requires no operator in the crossbar toll area. Assume the call is to the Philadelphia number Market 1234. The distant operator will key or dial MAR-1234. The crossbar equipment will use the MAR (627) to select an idle trunk to the Market local office and the remaining digits to drive switches in that office to the called subscriber's line. The connection will be released at the end of conversation when the distant operator releases her connection.

An inward call over a ring-down toll line is represented by Figure 6. In response to ringing current on the toll line, a cordless position will be connected automatically to the line. An operator at the position will receive the order for Market 1234 and will key the complete number—MAR-1234—on her keyset, causing the connection to be established as described. Her position is then released from the connection. Since the ring-down line can give no indication at the inward end that it has been released at the outward end, the toll crossbar equipment must recognize the called subscriber's hang-up in order to release the connection. This is done by equipment in the relay circuit associated with the incoming toll line, which times for two seconds after he hangs up, and, if he has not again removed his receiver from the switchhook, releases the connection. If the called subscriber flashes, if his line is busy, if he fails to answer, or if the outward operator rings on the toll line, an inward operator (not necessarily the one who originally handled the call) is again connected to the line, and lamps on her position indicate what action should be taken.

THROUGH CALLS

The method of handling incoming calls that are to be switched through the office to other toll lines will be obvious from the foregoing explanation. The need for an operator in the crossbar toll office is determined only by the nature of the incoming line. She is not needed when the incoming line is of the dialing type, regardless of the type of outgoing line to be selected. Through traffic is illustrated diagrammatically by Figure 7.

Transmission Aspects

All the longer toll lines of the Bell System are four-wire, that is, opposite di-

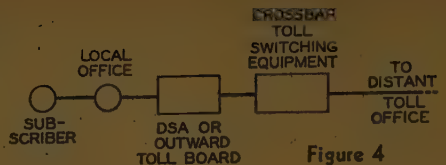


Figure 4

rections of transmission are over separate paths, each with one-way amplifiers at suitable intervals. These two paths are combined by means of a hybrid coil into a single two-wire circuit before reaching the telephone at each end.

At switching offices in this country, all four-wire circuits have been previously reduced to two-wire by a hybrid coil before they reach the switching point and thus have been switched as two-wire circuits. This is indicated in Figure 8a which shows a four-wire toll line at the left switched to a two-wire toll line with a terminal repeater. There are limits to the transmission efficiency of such arrangements, since the two-wire junction permits speech currents traveling in one direction to be reflected partially toward the talker at the hybrid coil, thus causing echoes. When there are two-wire junctions at both ends of the circuits, there is a closed path around which "singing" may result. In addition, when cord circuit repeaters are added at a two-wire switching point there is a two-wire junction on each side of the repeater, and more echoes result—being made greater by the gain of the repeater. A similar result is obtained at a "switching-pad" office when gain is effectively inserted by removing two-wire switching pads instead of by adding a repeater. Since any circuit in the office must be capable of connection to any one of a large number of other circuits, which may not all have the same characteristics, the balancing network at the junction obviously cannot be made to balance accurately all of them individually. As a result, a "compromise" network is employed. A two-wire switching point, where cord circuit or terminal repeaters are employed, is thus always a potential source of echoes because of the necessity of using compromise networks. Where the network is associated with a single circuit, on the other hand, as at the extreme right of Figure 8a, a precision network is used which greatly reduces the echo volume.

With the new crossbar system all lines are terminated on a four-wire basis at the switches as shown in Figure 8b. When these lines are four-wire circuits, this is done by omitting the terminating sets with hybrid coils that would normally be used to bring them down to a two-wire circuit, and by changing the signaling



Figure 5

means, switching pads, operators' connections, and other circuit elements to a four-wire basis. On the two-wire toll lines with terminal repeaters the same general result is obtained by removing the hybrid coil on the office side of the repeaters. On two-wire toll lines without terminal repeaters, a hybrid coil is added with one two-wire branch toward the two-wire line and the other toward the balancing network, and with the four-wire branches connecting to the switches. The net result is the same as the two-wire repeated toll line in Figure 8b with the two amplifiers and switching pads removed.

When two four-wire or two-wire toll lines with terminal repeaters are switched together on a four-wire basis, all sources of echo in the switching office are eliminated. Some echo is of course returned from the hybrid coil connecting the two-wire repeater to the two-wire line, but this can be kept small by keeping the balancing between the precision network and its associated line high.

If the two-wire toll line of Figure 8b did not have terminal repeaters or switching pads, the switching pads in the four-wire toll line would be removed, thus effectively inserting gain in the over-all connection. Because of the high balance at the two-wire hybrid coil, considerable gain may be inserted in this manner, thus allowing greater loss in the nonrepeated two-wire circuit. This greater loss permits saving in copper and loading and frequently permits omitting a terminal two-wire repeater that would be required with a two-wire switching system.

With four-wire switching, therefore, certain of the two-wire lines, chiefly those that are not used as intermediate links in long built-up circuits, may be made of the high-loss type. If two of these high-loss lines are to be connected together directly, there may be too much over-all loss from subscriber to subscriber. To avoid this, repeaters are switched in, thus reducing the over-all loss. There are no objectionable effects because of echoes or singing because at the point where these repeaters are inserted the circuit is four-wire, and thus there are no hybrid coils to act as a source of additional echoes. The hybrid coils, where the four-wire circuit is connected to the outgoing two-wire line, are precision networks, and even with the additional gain the echoes do not become objectionable, the two-wire

balances with precision networks inserting loss in the echo returned toward the subscriber. The insertion of repeaters is done automatically depending upon markings associated with the two lines connected.

These high-loss two-wire lines may be lines to other toll offices or connecting trunks to local offices. The determination of which trunk should be high loss and which low loss depends upon the economy which may be obtained in outside plant and terminal repeaters compared to the cost of providing additional gain when it is required.

Switching pads are provided on four-wire toll lines and on two-wire toll lines with terminal repeaters to permit the loss to be adjusted for the different types of connections that may be involved. With two-wire switching, special hybrid coil arrangements and means for inserting or removing switching pads were necessary to permit satisfactory talking in both directions on four-wire circuits.

Potentially, four-wire switching offers considerable promise. The percentage of four-wire toll lines will increase in the future both because long circuits tend to increase at a greater rate than do shorter circuits and because the general use of carrier throughout the toll plant will tend to reduce the minimum lengths of four-wire toll lines which are economical. With four-wire circuits and four-wire switching in general use, many improvements in echo suppression and volume control would become possible and economical.

Progress of Calls Through the System

The manner in which a connection is established through the crossbar equipment may be demonstrated by pointing out the function of each item of equipment in Figure 3 as the call progresses. For this purpose it is not necessary to know the composition of the individual parts, which will be described later.

The crossbar switches on which the incoming trunks and toll lines are terminated are assembled in groups called incoming link frames, and those on which the outgoing trunks and toll lines are

terminated are called outgoing link frames. These two types of link frames are interconnected so that any incoming trunk or toll line may be connected to any outgoing trunk or toll line.

DIAL OR KEY-PULSING CALL

The example previously used of the subscriber in Philadelphia who has originated a toll call to Harrisburg 6-5432 may again be employed. The outward operator selects a "tandem" trunk connecting to the crossbar toll switching equipment. Relays associated with this tandem trunk in the crossbar system signal the sender link frame that an incoming sender is required. A controller circuit then becomes attached to the sender link frame and connects the tandem trunk through the frame to an incoming sender. The operator then keys or dials the code 321, which is assigned to the Harrisburg toll-line group. She also keys the called number 6-5432, and these digits as well as the code digits are recorded by the sender. The sender in turn obtains access to a marker and transmits the Harrisburg code to it. This code is registered and translated by the marker which causes a route relay in the marker to operate. This relay directs the marker to the proper trunk-block connector where the test leads for all the toll lines to Harrisburg are located. Upon gaining access to the connector, the marker selects an idle toll line and immediately makes that line appear busy to other calls.

To connect the tandem trunk to the selected Harrisburg toll line, the marker must identify the incoming and outgoing link frames on which these are located. The signal identifying the outgoing link frame is furnished to the marker over a lead from the outgoing toll line through the trunk-block connector, while the incoming link frame is identified by a signal which the marker receives from the tandem trunk over one of the leads through the sender link frame, and the sender.

The marker then gains access to the incoming and outgoing link frames involved and excludes all other markers from these frames. It then selects an idle path through these frames and operates the proper magnets of the crossbar switches

to establish the connection. After this the marker releases and disconnects itself from the incoming and outgoing link frames as well as from the sender and the trunk-block connector. The total time required for the marker to perform all its functions is about one second.

When the toll line to Harrisburg has been selected, an outgoing sender will become associated with it through a sender link frame under the direction of a controller. The incoming sender will then transfer the called number to the outgoing sender, and that sender will control the switching equipment at Harrisburg through which the call is completed. Upon completion of their functions, the incoming and outgoing senders are dismissed.

RING-DOWN CALL

When, as in the case of the call to Chicago, the outgoing toll line is arranged for ring-down operation, the outgoing sender is not used. The operator will key only the code number of the toll-line group. This is sufficient to cause the call to be routed to the Chicago toll line as described for the previous call. A ringing signal is then transmitted by relay equipment associated with the toll line to signal the Chicago operator.

CALLS REQUIRING OPERATOR ASSISTANCE

Incoming calls from ring-down toll lines require operator assistance at the crossbar toll office as previously mentioned. An incoming signal from such a toll line causes the line to be connected through an operator link frame to an operator position. This position is of the cordless type and is equipped only with keys and lamps. The operator is automatically connected to the toll line and receives the necessary details of the incoming call from the outward operator. She then operates keys which cause the called number to be registered in a sender associated with the position. This sender is then associated with a marker, and the call is completed in the manner previously described.

In general, the operator at the crossbar toll office is released from the call as soon as the positional sender has completed its functions. If the call is not completed, as when the called subscriber's line is busy, an operator is reconnected to the call, and the status of the call is indicated by lamp signals at the position. The operator then makes the proper oral report to the calling operator. If the crossbar toll operator is required to take further immediate action on a call, the operator may remain associated with the

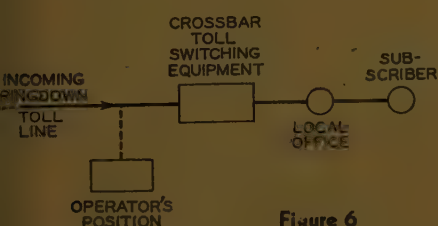


Figure 6

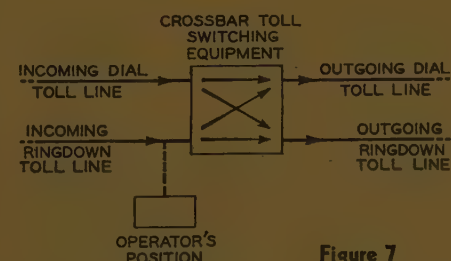


Figure 7

call even after the called number has been registered in the positional sender. This is accomplished automatically under conditions always requiring this association, or the operator may operate a key to retain association with the call.

THROUGH CALL REQUIRING A SWITCHED-IN REPEATER

If an incoming call from either a dial or ring-down toll line is switched to another toll line of either variety and both lines are high loss, a switched-in repeater is required. The marker is told by a d-c potential on a lead of the incoming line that it is high loss and by a contact of the route relay associated with the outgoing toll-line group that the outgoing line is high loss. Under these conditions, as soon as the marker has established the connection, it will send a signal to the outgoing line which will cause it to call for a repeater. A controller will thereupon be attached to the repeater link frame on which the outgoing line appears and will insert a repeater in the connection. The marker and controller are released as soon as their functions are completed, and the repeater remains connected for the duration of the call.

Principal Elements of the System

1. INCOMING AND OUTGOING LINK FRAMES

A "frame" is an assembly of switches interconnected as an electrical unit to serve a group of either incoming or outgoing lines. The incoming and outgoing link frames are composed of a primary and a secondary bay of switches, each ten switches high, with as many supplementary bays as are required to accommodate the number of trunks necessary to make efficient use of the call-carrying capacity of the frame. Incoming trunks appear on the primary and supplementary primary bays of the incoming frames, and outgoing trunks appear on secondary and supplementary secondary bays of outgoing frames. Each bay has a capacity of 100 trunks. The links connecting the primary and secondary bays are called *A* links, those connecting the secondary bays of the incoming frames and the primary bays of the outgoing frames are called *B* links or junctors, and those connecting the primary and secondary bays of the outgoing frames are called *C* links. Each incoming frame has connections to all outgoing frames but none to other incoming frames, and the reverse is true of outgoing frames. A simplified schematic diagram of the arrangement is indicated in Figure 9.

It will be noticed that *A* and *C* links interconnect switches on a frame, while *B* links interconnect frames. The pattern of *A* and *C* links is fixed, and there are always 200 on a frame in ten groups of 20 each, so that each trunk has access to 20 *A* or *C* links. While the distribution of *B* links follows an orderly pattern, it will vary with the number of frames, which is, of course, dependent upon the size of the office.

There are always at least 20 *B* links from each incoming frame to each outgoing frame and therefore 20 paths by which an incoming trunk can reach a particular outgoing trunk. Each path consists of three links in series, and between any one incoming and any one outgoing line, a particular *A* link can be used with only one particular *B* and *C* link, and thus, if one is busy, the entire path is unavailable for use on the call. The method of selection employed by the markers is such that the lowest numbered path, all elements of which are idle, is used. This is the simplest method and has the additional advantage of giving a lower probability of blocking a call because of inability to match links than would a random choice of links.

Since there are only 200 *B* links per frame and 20 links to each opposing frame

coming frames and 20 outgoing frames is comparable in size to a 10,000-line local crossbar office.

In the Philadelphia installation it was found desirable to provide two separate trains of switches, one for outward and through traffic, the other for inward traffic. The system is described in this paper, however, as a single train system, since all that is required for a clear understanding of its operation may be presented on that basis.

2. OPERATOR LINK FRAMES

As shown in Figure 3, an operator link frame is used to connect incoming manual trunks to operators' positions. It is composed of 100-point (ten by ten) crossbar switches in primary-secondary alignment and accommodates 100 trunks on the primary side and 40 cordless positions on the secondary side. Each group of ten trunks is served by four links, each of which gives access to ten positions. Figure 10 depicts half an operator link frame, the other half being an exact duplicate of it with the trunks multiplied to both halves.

The establishment of connections through operator link frames is directed by a group of controllers in much the same manner as the markers direct connections through incoming and outgoing frames. The controllers gain access to trunks, links, and positions through controller connectors consisting of multicontact relays.

To obtain substantially uniform treatment of calls and particularly to guard against "orphan calls," the "gate" principle of serving them is employed. When a controller is attached to a link frame, it scans the ten subgroups of trunks and admits within the gate all which have at least one waiting call. Those which have no waiting call will be locked outside, and calls which may subsequently arrive on them will not be served until the frame has been released and has secured a new controller. The controller then selects one of the admitted subgroups and locks out the individual trunks of that subgroup which do not have waiting calls. Having served all accepted waiting calls in that subgroup, it proceeds to the next subgroup, treats it in the same manner, and so continues until all subgroups admitted within the gate have been served. It then releases the frame and so marks it that it will not again serve that frame until all other frames having calls waiting at that time have been served. When operators are available, the time required to serve a call is less than a second.

Several precautions are taken to insure

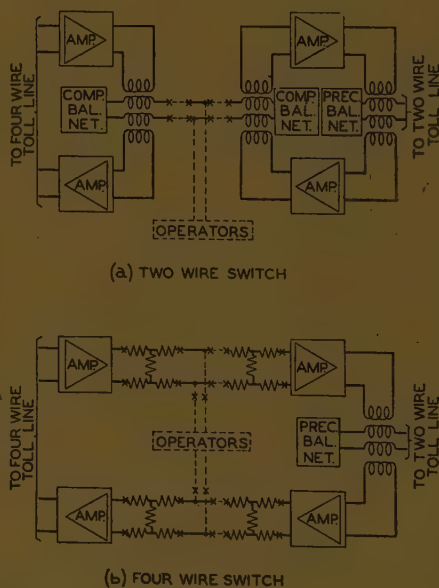


Figure 8. Typical transmission paths through switching offices.

are required, the size of an office would seem to be limited to ten incoming and ten outgoing frames. This limit is extended to 20 of each, however, by the simple device of providing a supplementary bay of secondary switches on incoming frames, and by multiplying *B* links on pairs of frames so that each may share the links of the other. An office with 20 in-

even distribution of the load to operators:

- A standard pattern for cabling positions to link frames has been carefully constructed with that end in view.
- Half of the controllers test for idle positions in one direction, the other half in the opposite direction.
- The position appearances on the frames are divided into small groups, and a controller starts testing with a different group on each call until a complete cycle has been made.

3. SENDER LINK FRAMES

Sender link frames are similar to operator link frames and are used to give access to both incoming and outgoing senders. Two-way dial toll lines appear only on incoming sender link frames and obtain access to both types of senders through them, a portion of the outgoing senders being multiplied to some incoming sender link frames for that purpose. The connections through sender link frames are directed by controllers in the manner described for operator link frames.

4. REPEATER LINK FRAMES

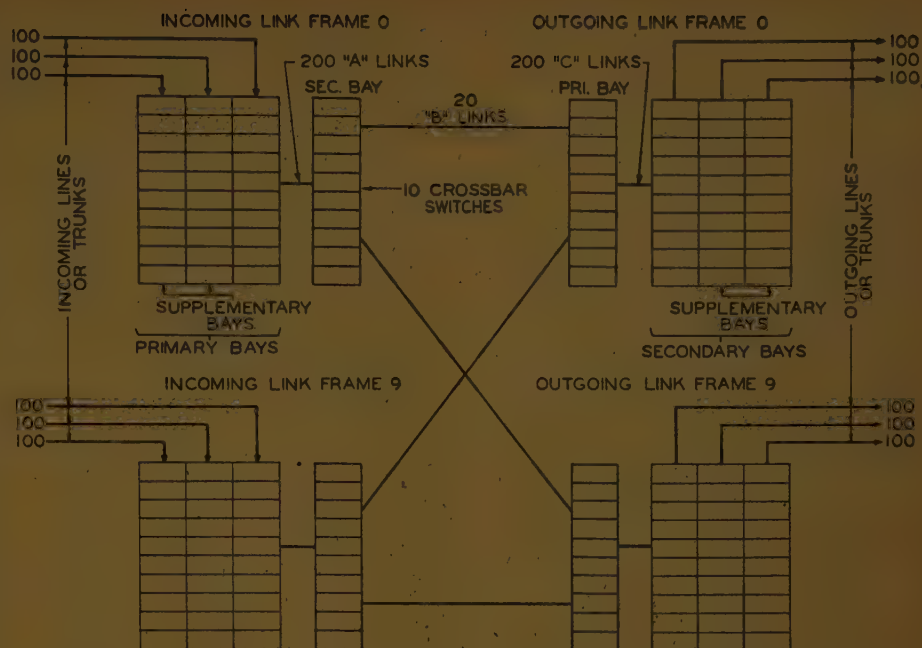
Repeater link frames are similar in construction and operation to operator and sender link frames but provide 60 links giving access to 60 repeaters to serve 100 outgoing toll lines. The greater link capacity is required because the repeaters are held for the duration of the conversation.

5. CORDLESS SWITCHBOARD POSITIONS

The switchboard positions are of the cordless type, all functions performed by the operator being effected by key operations. The physical appearance of the switchboard is shown in Figure 11.

Calls reach a position through three channels known as loops, and it is the loops which appear on the operator link frames. Triplicate channels are provided to permit calls which require continuing attention by the operator to be held on the position and to permit overlap operation, that is, the admission of a new call to a position before complete disposition has been made of a previous call. Each loop appears on the position as a key and three associated lamps. Normally calls are connected to the operator's telephone circuit automatically, but, when a loop is held to her position, she may connect her telephone circuit to it at will, and the key is provided for this purpose. The lamps are:

- A guard lamp which flashes when the loop is connected to the operator's telephone circuit.
- A busy lamp which is lighted steadily



as long as the loop is held to a trunk through the link frame.

- A supervisory lamp which follows signals received from the called trunk.

A complete sender is associated with each position and appears on the marker connector frame for connection with the marker. To permit overlap operation, however, the sender is actually divided into two parts, that part concerned with the code digits being associated with the operator's telephone circuit and the remaining part functioning independently as a normal incoming sender. The two parts may be simultaneously connected to two different trunks through two of the position loops.

The keyset used by the operator in pulsing consists of 11 strips of ten-button keys and a start key. The setting of the first three strips is transferred to the marker for selection of the called trunk, and that of the remaining strips is transmitted to an outgoing sender, or to a sender in a distant office if the outgoing trunk is to an office equipped to receive a-c key pulses.

A number of lamps and keys common to the position are provided to apprise the operator of the proper course of action to be followed and to enable her to take the necessary action to meet the various conditions which are presented to her.

6. SENDERS

The function of a sender is to accept incoming pulses, interpret them, register them as numerical digits, and transmit them forward for the purpose of controlling switching operations. The wide variety of trunks which must be inter-

Figure 9. Links between incoming and outgoing trunks

connected by this system has made it advisable to provide separate incoming and outgoing senders, and to transfer to the outgoing senders those digits which must be used to control switching operations in distant offices. Although this method of operation results in several types of senders in the office, each sender is less complicated, since it may be arranged for only the kind of pulsing required by the trunks with which it is associated. Outgoing trunks arranged for a-c key pulsing do not require an outgoing sender, the pulses being sent from the incoming sender directly to a receiving sender in the distant office.

There are two groups of incoming senders, one arranged to receive dial pulses, the other to receive a-c or d-c key pulses. Both are arranged to transmit either d-c pulses to an outgoing sender in the same office or a-c key pulses to a sender in a distant office. D-c key pulsing represents digits by combinations of high and low conditions of two polarities of battery over two wires and ground and is limited to use between items of equipment in the same building. A-c key pulsing employs combinations of frequencies in the voice range, and may be used for any distance. The key-pulsing senders are signaled by a d-c potential on a lead of the incoming trunk whether to prepare for reception of a-c or d-c pulses.

There are also two groups of outgoing senders, one arranged to transmit either the type of pulses required by the equipment in local panel offices or the type used to reach manual offices in a panel area, the other to transmit either dial pulses

of the type used to drive step-by-step equipment or call announcer pronouncements to manual offices equipped for their reception. A d-c potential on a lead of the outgoing trunk tells the sender which kind of pulsing to transmit.

7. MARKER CONNECTORS

Marker connectors give incoming senders and cordless position senders access to markers. They are composed of multi-contact relays. One marker connector frame gives 18 senders access to all markers through two separate channels. Each sender, therefore, appears twice on marker connectors and each marker as many times as there are marker connectors.

8. TRUNK-BLOCK CONNECTORS

A group of outgoing trunks to a particular destination is spread evenly over outgoing frames. To enable the marker to test the desired group and select an idle trunk, however, it is necessary to assemble test leads representing the group at some point. The sleeve and select magnet leads of all trunks are brought to the trunk-block connector for this purpose.

A single connector accommodates 400 trunks with duplicate appearances and gives all markers access to them. A block consisting of 40 trunks may be a complete trunk group so far as destination is concerned, only part of a group, or several groups.

The select magnet lead which is brought through the trunk-block connector carries information to the marker identifying the location of the trunk on the outgoing frame. Since it is frequently necessary to make temporary reassignments of toll lines, the trunk-block connector is supplemented by assignment patching jacks through which the sleeve and select magnet leads of many toll lines are carried.

9. MARKERS

The several hundred relays comprising the marker, which is the "brains" of the system, form a number of related but somewhat independent groups with different duties to perform. Only the more important of these will be discussed.

One group of relays checks the integrity of the leads between the incoming sender and the marker. A second group registers the three digits comprising the code for the outgoing trunk group. A third group, part of which are of the multicontact class, serves to convert the three-digit registration into the marking of a single terminal which may be cross-connected to a route relay representing a

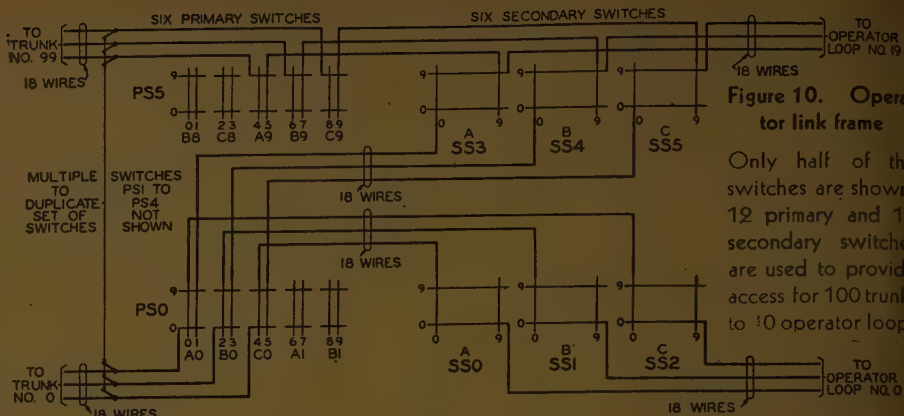


Figure 10. Operator link frame

Only half of the switches are shown, 12 primary and 12 secondary switches are used to provide access for 100 trunks to 10 operator loop.

particular outgoing trunk group. These route relays constitute another group.

Each marker is equipped with a route relay for each trunk group to be reached. The route relay carries contacts which are connected to punchings providing information as to the nature of its associated trunk group and the means of locating it. Some punchings guide the marker to the selection of the trunk block on which the group appears and tell it where to begin and end testing of the trunks in the block. Others tell it whether the trunks are of a variety requiring the insertion of voice repeaters on some connections and supply information to control the action of incoming senders and cordless positions.

In another group 40 relays are simultaneously connected to the sleeve leads of the trunks through the trunk block in order to select an idle trunk in the desired group. Another group of relays tests *A*, *B*, and *C* links, matching them for an idle path through the switches of the incoming and outgoing frames. A chain of 20 pairs of multiwound relays is used for this purpose. In setting up a connection, an *A*, a *B*, and a *C* link in series form one channel, and a set of this sort is connected to three of the windings of each pair of test relays. If any winding is energized, the associated channel is unavailable for use on the connection. The first pair of relays in the chain remaining unoperated selects the channel to be used.

A set of vacuum tubes and filters is used for frame identification, that is, for determining on which frames the two trunks to be interconnected are located. This information is presented to the marker in the form of three frequencies imposed on the select magnet leads of the trunks. The frequencies used are the odd harmonics of 85 cycles from 425 cycles to 1,615 cycles.

A-C Key Pulsing

One of the interesting new features of this switching system is the use of a-c key

pulsing to transmit digits over toll lines. Exchange names and subscribers numbers have previously been transmitted by d-c key pulsing within an office, but this is not practicable for transmission over long toll circuits. A-c key-pulsing signals, however, can go wherever the speech currents can go and at the same speed, so there is no limit on the range of this method.

When an operator uses a suitable key-set or when the sender recognizes by suitable marking that the circuit over which it is to send a number is equipped for a-c key pulsing, a *KP* signal is sent out which consists of 1,100 cycles and 1,700 cycles, simultaneously. At the distant end, the reception of the two frequencies makes the a-c key pulsing receiver sensitive to further signals. The numbers or letters are then sent one at a time, each represented by two of the frequencies 700, 900, 1,100, 1,300, and 1,500 cycles. Finally, a signal consisting of 1,500 and 1,700 cycles simultaneously is sent to indicate the end of the number and to make the receiver insensitive again. The receiving sender then proceeds to set up the call.

The receiver is insensitive to other currents such as noise or speech, except during the interval while the signals are being sent. To avoid a false *KP* signal and to protect against wrong numbers during the sensitive interval, the receiver is arranged so that two and only two frequencies can indicate a number. If the proper signals are not received, supervisory signals are sent back to notify the operator originating the call by a flashing light that she must put the call through again.

By a-c key pulsing, it is possible to transmit numbers over any satisfactory telephone circuit faster than any operator can send them. An incoming dial sender of the new system, for example, receives numbers from an operator at the calling end of the trunk at the rate of about one digit per second, while it will send numbers over the outgoing trunk at the rate of ten digits per second. The

use of pulsing also gives a one-way check of the transmission continuity of the toll line.

Facilities for Handling Delayed Traffic

The cost of long-distance circuits has to date rendered it imperative to engineer them on a delay basis in order to maintain toll service at a reasonable cost to the subscriber. This means that in the busy hours, calls will frequently encounter "no-circuit" conditions. Under such conditions it becomes desirable to relieve operators of the burden of making repeated unsuccessful attempts to secure a circuit. This purpose is accomplished by means of overflow circuits.

An overflow-control circuit is associated with each toll-line group appearing on outgoing frames and permits a maximum of from one to four simultaneous connections to it depending on the size of its associated toll-line group. The trunk circuits affording entrance to the overflow-control circuit appear on the trunk-block relay along with the associated toll lines. A call for a group having all circuits busy is connected to overflow. As long as all circuits are busy, the overflow circuit returns a slow flash to all incoming circuits connected to it, and, when a circuit becomes available, a fast reorder flash is returned. If all circuits of a group are busy and all of its associated overflow trunks are also busy, the call will be routed to one of a group of master busy trunks common to the office. Master busy trunks return a distinctive irregular flash.

The flashes are returned to the originating operator on calls employing dial toll lines or tandem trunks. On calls coming in over ringdown toll lines, the cordless operator is held if the connection is routed to overflow. She is given a lighted overflow pilot lamp, and the loop is automatically locked to her position so that she may subsequently take action when a circuit becomes available.

Occasionally in normal times, very heavy overloads of traffic on some groups occur because of holiday demands or unpredictable catastrophes. Under war conditions these overloads occur rather frequently. When they occur, calls tend to accumulate in quantities which will tax the capacity of an affected trunk group for extended intervals.

Under these conditions, facilities are required to enable the operating force to serve calls as nearly as practicable in order of their filing time. For this purpose, a manual call-order board is provided.

This board is similar to other cord switchboards except that twin plugs and jacks are used so that through calls may be established on a four-wire basis. The call-order operator establishes a through connection by first plugging one end of a cord into a tandem trunk and keying over it to secure the toll line, then repeating the operation with the other end of the cord to secure the other toll line. Her position is equipped with a ten-button keyset. Whenever circuit groups become so congested that calls cannot be served within five or ten minutes, call orders for through calls are assembled at the call-order board.

When congestion develops to the point where delay must be quoted, a patch is made from the overflow-control circuit to a delay-quoting trunk appearing in the call-order switchboard. As long as connections are in overflow, a call-order operator will repeatedly quote the delay indicated by the trunk. When the patch has been made, all operators except those at the call-order board are denied access to the group. The outward operators in the same toll-center area must then leave requests with the call-order operators to secure circuits for them.

Maintenance Facilities

Perhaps the most interesting of the maintenance facilities is the marker trouble indicator. When a marker encounters trouble in the process of setting up a connection, it calls in the trouble indicator and leaves a record of the trouble. The record is displayed on lamps which indicate how far the marker had progressed with the call, what individual equipment items had been involved, and, where possible, the nature of the trouble encountered.

A similar trouble indicator on a smaller scale is provided for controllers. Automatic routine testing equipment for senders and outgoing trunks is also provided.

The new toll testboard associated with the system carries twin-jack appearances of toll lines to permit four-wire switching. It is also equipped with dialing and key-pulsing apparatus to enable it to operate with the mechanical equipment.

Traffic Meters

A comprehensive set of measuring apparatus is provided to keep the supervisory force informed as to the performance of the office. This equipment, consisting of ampere-hour meters, ammeters, recording ammeters, message registers, and lamps records traffic load carried by various elements of switching equipment, de-

layed calls, and other items of interest to the office management and to the traffic engineer.

Conclusion

The new switching system offers many improvements over the switching equipment which has been in use in the large toll centers in the past.

Transmission objectives are met with greater ease, and substantial economies are made in the outside plant and in repeater equipment.

It provides facilities which enable outward toll operators to direct the establishment of connections without the aid of inward or through operators. This results in operating economies and improved service to the subscriber. The provision of a cordless switchboard to handle traffic which must remain for some time on a ring-down basis enables that traffic also to be handled more expeditiously and with operating economies.

The use of senders and markers for controlling the establishment of connec-

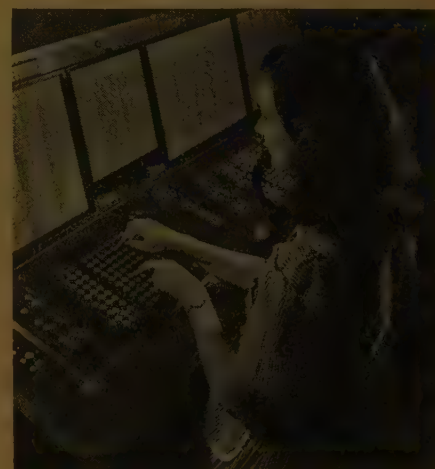


Figure 11. Cordless switchboard

tions will undoubtedly play an increasingly important part in future long-distance switching, since these devices permit more complete mechanization of the long distance operating job. The switching system which has been described is, therefore, inherently well adapted to meet the future requirements of the continually improving long-distance-switching network now functioning in the United States.

Reference

1. CROSSBAR DIAL TELEPHONE SWITCHING SYSTEM, F. J. Scudder, J. N. Reynolds. AIEE TRANSACTIONS, volume 68, 1939, May section, pages 179-200.

Regulation of A-C Generators With Suddenly Applied Loads

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DETERMINATION of the voltage drop at the terminals of small generators during the starting of relatively large motors has long been an important problem, particularly in connection with the starting of large motors on power-house auxiliary generators. Interest in this problem has been greatly accentuated by the wartime application of many small a-c generators, in fixed and mobile locations, supplying motors of ratings amounting to an appreciable fraction of the generator rating. It is essential in such applications to be able to predict accurately the maximum voltage drop in order to be sure that motor starters on the line will not drop out and that motors already running will not stall when large additional loads are started. Other types of apparatus are critical to low voltages of short duration, particularly if such low voltages recur frequently.

A practical method¹ has been available for some time for determining generator voltage-time curves following the sudden application of load. In this method the voltage-time curve is constructed by a step-by-step graphical process. In this paper equations are derived that yield directly the minimum voltage of the voltage-time curve. The calculation of a large number of specific cases using both these methods has indicated that many of the factors that enter theoretically into the problem have practically a small effect on voltage drop, and that by using average or typical values for the factors of small importance, the maximum voltage drop during motor starting can be expressed in curves in terms of only a few important parameters.

A general study has been made to determine the effects of varying independently

all of the factors entering into the regulation problem. This study demonstrates conclusively that average values can be used for the less important factors. As a result it has been possible to present sets of curves that show with accuracy the maximum voltage drop to be expected when motors of any size are started on generators of various characteristics. These curves can be used without involved calculation and with a knowledge of only the most essential factors, entering into the problem; namely, the full voltage inrush current of the motor, the transient reactance and the open-circuit time constant of the generator, and the response of the exciter. Tables are included to show the average values of these various constants for generators and exciters commonly used; therefore, a fairly good approximation to the maximum drop can be obtained from the information given in the paper without detailed information regarding the equipment involved.

Curves of Maximum Voltage Drop

The final results of the studies described in this paper are the maximum-voltage-drop curves, Figure 1, for suddenly applied low-power-factor load. The curves apply to a regulating system having essentially the elements shown in Figure 2. A direct-acting regulator varies resistance in the field of a self-excited exciter to regulate the a-c generator voltage. This system of regulation is the one most commonly used with a-c generators ranging in size from the smallest up to machines of several thousand kilovolt-amperes. While the curves were calculated for machines having self-excited exciters, they apply approximately in the case of large machines having separately excited exciters.

Figure 3 is a typical curve of the voltage-time behavior of a generator under suddenly applied load. The calculated points of this figure were obtained by means of equations derived in a later section of this paper. When a low-power-factor load is suddenly thrown on a generator, the terminal voltage drops suddenly as shown in Figure 3 be-

cause of internal reactance drop and then begins a gradual drop to a much lower value because of armature reaction. The initial drop initiates action of the voltage regulator, which removes resistance from the exciter field. This causes the exciter voltage to begin building up, stopping the downward trend of generator voltage and bringing this voltage back to normal. The most important single feature of this "voltage-dip" characteristic is the maximum drop reached. Entire dips involve times of 0.5 to 1.5 seconds, and the voltage is near its minimum value for several cycles. Consequently, the maximum drop, reached at the low point of a dip, is the criterion of undesired starter dropout, motor stalling, and other phenomena associated with low voltage. It is this maximum drop that has been plotted in the curves of Figure 1.

The curves of Figure 1 show the maximum voltage drop as a function of the amount of low-power-factor load added directly at the generator terminals for a wide range of values of generator transient reactance. Families of curves of this type are given for various generator time constants and exciter responses. Table I shows probable minimum, maximum, and average values of the generator reactances affecting voltage drop. Figure 4 shows typical time constants of machines of different sizes and speeds.

A summary of the basis for the curves of Figure 1 is given in Table II. Although derived on the basis of no initial load, the curves apply well for the mixed static and rotating initial loads usually encountered. The curves were calculated under the assumption of 35 per cent power factor for the applied load. This is a typical starting power factor for squirrel-cage induction motors, and as shown in a later section wide variations in power factor from this typical figure will have little effect on the maximum drop.

In the determination of maximum voltage drops from Figure 1, applied loads should be expressed in terms of per cent generator current at full voltage. In the calculation of the curves the added load was treated as a fixed impedance. The impedance of a normal induction motor is fairly constant at the locked-rotor figure at speeds up to at least 75 per cent of full speed, and a loaded induction motor will not normally reach this speed during the short time required for the regulator to stop the downward trend of generator voltage; therefore, in determining maximum drops from Figure 1, induction motors can be assumed without signifi-

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Development of the mathematical method for the determination of maximum voltage drops is abstracted from a thesis, "Suddenly Applied Loads on Generators With Quick-Response Excitation," by R. C. Cheek, submitted to the University of Pittsburgh in partial fulfillment of the requirements for the degree of master of science.

ant error to be fixed impedances during the starting period.

Example: Suppose a 50-horsepower 440-volt induction motor, having 600 per cent starting current at full voltage, is to be started across the line on a 500-kva generator of 30 per cent transient reactance. Full-load kilovolt-ampere input for a typical motor of this size is 48.2 kva. The full-voltage starting inrush is therefore $48.2 \times 6 = 289.2$ kva or 58 per cent of generator rating. With a generator time constant of 2.0 seconds and an exciter response of 1.0 or higher, the maximum drop according

to Figure 1 is 17.5 per cent, or in other words the minimum voltage is 82.5 per cent. This provides considerable margin above contactor-dropout voltages of 65 to 70 per cent and the 70 per cent voltage at which a fully loaded motor of 200 per cent pull-out torque would stall if it were already running on a line supplied by the generator.

Factors Influencing Voltage Regulation

The maximum voltage drops have been given as functions of four principal pa-

rameters; namely, added load, generator transient reactance, generator time constant, and exciter response. There are a number of other factors entering into the equations for maximum voltage drop, but as will be shown these are generally minor factors, which can justifiably be represented by average values in determining voltage drops.

In this section all of the various factors that affect the terminal voltage of a generator during the starting of a large

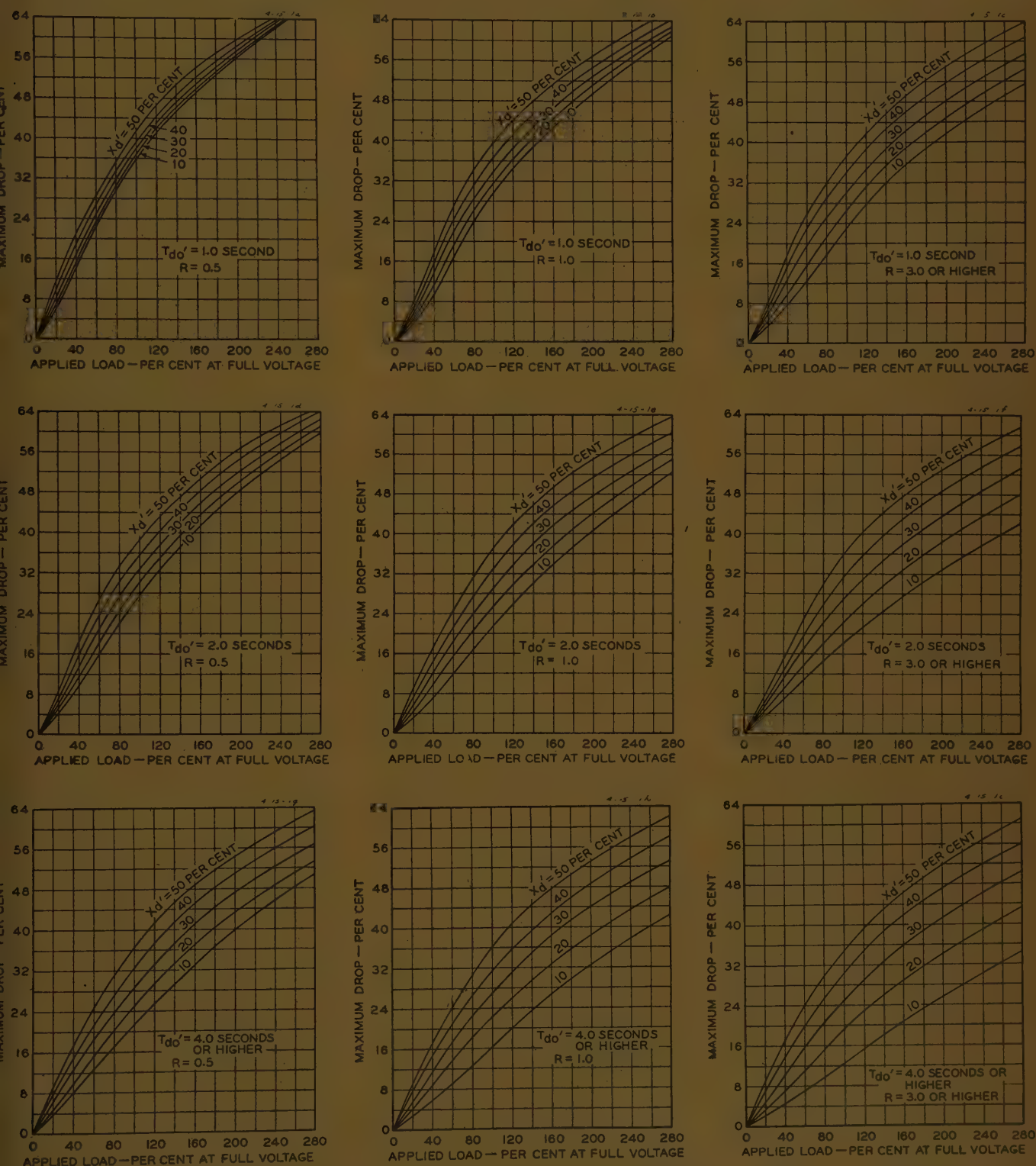


Figure 1. Voltage drop versus suddenly applied load for generators with various transient reactances, x_d' , time constant, T_{do}' , and nominal exciter response, R

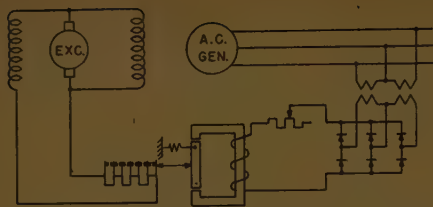


Figure 2. Essential components of excitation system with direct-acting regulator and self-excited exciter

motor or other load are discussed. These are taken up in order, consideration being given first to generator characteristics; second, to exciter characteristics; third, to voltage-regulator characteristics; and fourth, to the characteristics of the load itself. In each case, to show the effect of a particular quantity, all other quantities have been held constant at the average values shown in Table II while the one quantity under discussion was varied. In general, the voltage drop is but little affected by variations of the minor parameters. However, from the curves given in this section, approximate corrections can be made for these lesser variables where such corrections are warranted.

GENERATOR TRANSIENT REACTANCE, x_d'

The curves of Figure 1 are plotted in terms of the saturated or rated-voltage value of transient reactance, $x_d'_{sat}$, which is the value customarily supplied by the manufacturer as the transient reactance, x_d' , of the machine.

Actually two different transient reactances are recognized by the AIEE. The rated-voltage transient reactance is measured by short-circuiting the machine at normal voltage, no load. The test involves a transient current of, for example, four times normal current for a machine of 25 per cent transient reactance. Since such currents introduce considerable saturation, the test gives a somewhat lower reactance than would be effective during motor-starting duty on the generator.

The rated-current transient reactance, on the other hand, is measured with the machine voltage reduced at no load so that the transient current drawn on short circuit is just full-load current. Because of the low voltage used in this test, about 25 per cent of normal for a machine of 25 per cent transient reactance, the degree of saturation is less, and the reactance measured is consequently somewhat higher than is effective under motor-starting duty.

The transient reactance effective under usual motor-starting conditions lies between the rated-voltage and rated-cur-

rent transient reactances. It has been found from test and also by analysis to be greater than the rated-voltage value by approximately one third of the difference between the rated-voltage and rated-current values. Figure 5 shows a test curve of generator voltage under suddenly applied load without regulator action. Calculated curves based on rated-voltage and rated-current values of reactance, $x_d'_{sat}$ and $x_d'_{unsat}$, show that calculations based on a reactance greater than the rated-voltage value by one third of the difference between the rated-voltage and rated-current values would practically have coincided with the test curve, except for the initially high subtransient component that appears in the test curve. The subtransient component was neglected in the two calculated curves and elsewhere in the paper be-

Table I. Typical Values of Principal Factors Affecting Voltage Drop*

	x_d	$x_d'_{sat}$	x_p
Two-pole turbine generators.....	1.10	0.155	0.09
	0.95-1.45	0.12-0.21	0.07-0.14
Four-pole turbine generators.....	1.10	0.23	0.17
	1.00-1.45	0.20-0.28	0.12-0.24
Salient-pole generators.....	1.15	0.37	0.32
	0.60-1.45	0.20-0.50	0.17-0.40
Exciter response.....		1.0	
		0.5-3.0	
Regulator operating time, seconds.....		0.05	
		0.03-0.10	

* Reactances are per unit. Values below the line give the range of values, while those above give an average value.

Table II. Summary of Basis of Curves of Figures 1 and 6

The curves of Figure 1 are based on average constants and assumptions as follows:

- Direct-axis transient reactance x_d used in calculation = $1.07x_d'_{sat}$.
- Direct-axis synchronous reactance $x_d = 1.20$ per unit
- Quadrature-axis synchronous reactance $x_q = 0.75$ per unit
- Excitation required for saturation at no load, normal voltage — 0.20 per unit
- Regulator equivalent operating time — 0.05 second
- Added load — constant impedance, 0.35 power factor
- Initial load — zero
- Regulating system — shown in Figure 2

The curves of Figure 6 are based on the foregoing assumptions and in addition the following, except for the one parameter varied in each case:

- $x_d'_{sat} = 0.25$ per unit, $x_d' = 1.07 \times x_d'_{sat} = 0.268$ per unit
- $T_{do}' = 3.0$ seconds
- Exciter response = 1.0
- Added load — a 0.35 power-factor impedance which would draw 100 per cent of generator full-load current rating at normal voltage

cause subtransient effects are normally over before maximum voltage dips occur.

The ratio of rated-current to rated-voltage transient reactance varies from 1.14 for average standard machines to 1.3 or greater for more highly saturated lightweight machines built for mobile service. Thus, "greater by one third of the difference" means from 1.04 to 1.10 times the rated-voltage value, $x_d'_{sat}$. The curves of Figure 1 were calculated using a reactance of $1.07 x_d'_{sat}$.

Figure 6a shows the effect of generator transient reactance on maximum voltage drop for 100 per cent applied load. Doubling the transient reactance from 20 to 40 per cent multiplies the maximum drop by only 1.38. This illustrates the small error involved in the use of the curves of Figure 1 when the effective reactance for motor-starting duty is other than 1.07 times $x_d'_{sat}$.

GENERATOR SYNCHRONOUS REACTANCE, x_d , AND SHORT-CIRCUIT RATIO

As shown in Figure 6b, the maximum voltage drop increases with an increase in synchronous reactance. With the average generator and exciter characteristics upon which this curve is based, the change in maximum drop at 100 per cent applied load is about two parts in twenty five as x_d is varied from 120 per cent down to 100 per cent or up to 140 per cent. With 20 per cent saturation at no load, the corresponding variation in short-circuit ratio is from 1.0 up to 1.2 or down to 0.86. These variations from the average x_d of 120 per cent are as large as are usually encountered among normal machines, and the curves of Figure 1 can be used directly for normal machines without serious error for most purposes.

An accurate figure for maximum voltage drop may be required in some cases where generator synchronous reactance differs greatly from 120 per cent. The curves of Figure 1 can be used for the precise determination of drop in such cases by first expressing generator reactances and the applied load on a new kilovolt-ampere base, such that x_d on the new base is 120 per cent, and then applying the curves. For example, suppose a low-power-factor load of 1,500 kva (expressed at full voltage) is to be applied to a 3,000-kva generator having 30 per cent transient reactance and 150 per cent synchronous reactance. Suppose that the generator time constant is 4.0 second and the exciter has a nominal response of 1.0. To determine the drop, express the transient reactance and the applied load on the kilovolt-ampere base upon which x_d is 120 per cent. The base in this case

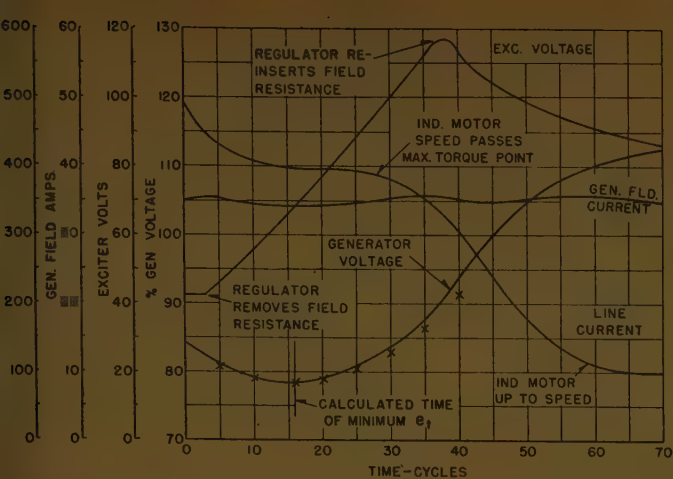


Figure 3. Typical voltage-dip curve obtained from test with calculated points (crosses) for comparison

Added load 0.97 per unit at 0.41 power factor to 375-kva generator initially operating at 0.20 per-unit load, 1.0 power factor

will be $3,000 \times 120 / 150 = 2,400$ kva. On this base the transient reactance x_d' is $30 \times 2,400 / 3,000 = 24$ per cent, and the applied load is $1,500 / 2,400 = 62.5$ per cent. From the curves of Figure 1, the maximum voltage drop is 15 per cent for 62.5 per cent load applied to a generator having 24 per cent transient reactance, a time constant of 4.0 seconds, and an exciter of 1.0 nominal response. This same maximum drop would be obtained with the machine and load under consideration.

GENERATOR OPEN-CIRCUIT TIME CONSTANT, T_{do}'

The maximum drop decreases as the time constant is increased, as shown in Figure 6c. In general, the time constant is longer for larger machines, typical values being given in Table I. In view of the relatively large effect of variations in this factor, it was selected as one of the four main parameters in the calculation of Figure 1.

GENERATOR QUADRATURE-AXIS

SYNCHRONOUS REACTANCE, x_q , AND SATURATION, s

As shown in Figure 6d, variation of x_q has practically no effect on the maximum voltage drop. This effect would be expected for low-power-factor loads, because for such loads practically all the phenomena take place in the direct axis, quadrature-axis effects being relatively unimportant.

The increased excitation required for saturation in normal machines as compared with that which would be required with no saturation enters into the voltage-drop calculation. An excitation at no-load normal voltage 20 per cent greater than that required to produce normal voltage on the air-gap line was used in calculating the curves. Figure 6e shows that the drop is not altered materially by varying this factor from zero to 40 per cent. The latter figure represents

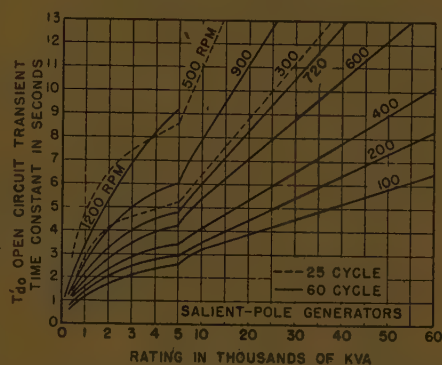
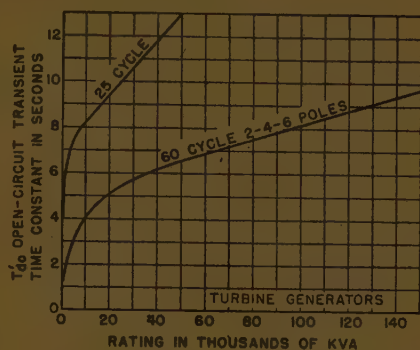


Figure 4. Typical open-circuit time constants of machines of different sizes and speeds

a machine having above-average saturation.

EXCITER RESPONSE

The voltage of a self-excited exciter builds up at an accelerating rate in an exponential curve until limited by saturation. The time constant of the exponential increase is directly related to response as defined by the American Standards Association, as will be shown in a later section. Below saturation the exciter voltage increases 2.718 times per time constant.

As shown in Figure 6f, maximum generator voltage drop is reduced sharply by an increase in response up to 1.0, but beyond this point the gain is not as pronounced. The curve is based on a generator time constant of 3.0 seconds. With shorter generator time constants, increases in the exciter response above 1.0

will reduce the drop more than indicated by the curve.

REGULATOR OPERATING TIME

After the voltage drops, the regulator requires a finite time to short-circuit the resistance in the exciter field circuit. While this is not an instantaneous process, an equivalent regulator operating time can be used with negligible error. Sudden short-circuiting of the resistance at the regulator operating time is equivalent to the actual gradual removal of resistance. The curves of Figure 1 are based on a "regulator operating time" of 0.05 second, a fairly representative value for the direct-acting-type regulator. As shown in Figure 6g the drop is increased only 0.7 per cent out of 25 per cent, if this time is doubled; consequently, no great error is made in using the curves of Figure 1, based on a regulator operating time of 0.05 second, for cases where operating time may be slightly greater or less than this figure.

INITIAL LOAD

The initial load on a generator influences the voltage drop when additional load is suddenly applied. As shown in Figure 6h, a static or constant-impedance initial load reduces the voltage drop caused by suddenly applied load. However, a load that draws additional current as voltage decreases may increase the voltage drop. Such loads will be referred to herein as "dynamic" loads. For example, a running induction motor may drop slightly in speed during the voltage dip so that it actually draws an increased current and thereby increases the maximum voltage drop. The dynamic initial load curve of Figure 6h is based on an initial load that draws constant kilowatts and power factor as the voltage varies.

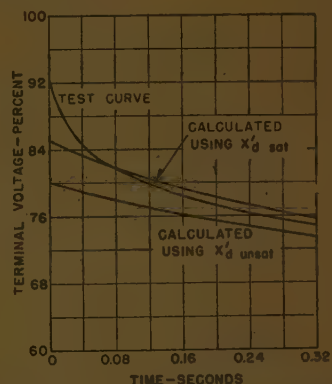
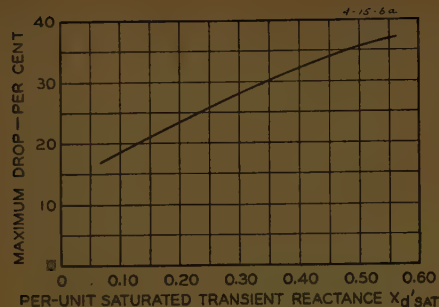
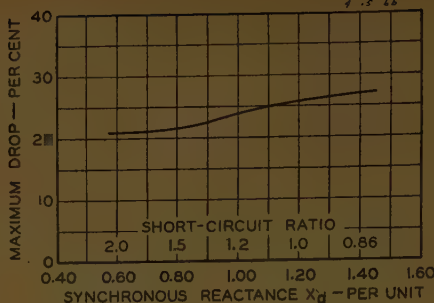


Figure 5. Test and calculated voltage-time curves of an a-c generator with a suddenly applied reactive load

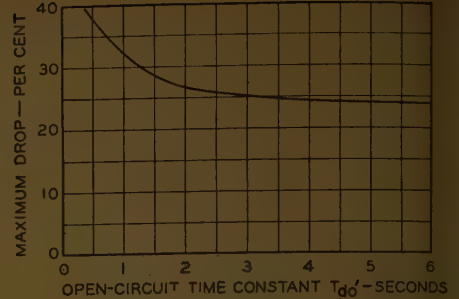
No regulator action. Subtransient effects were not considered in calculated curves



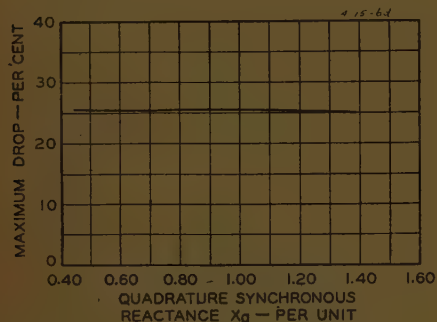
(a). Generator transient reactance, $X_d'_{sat}$



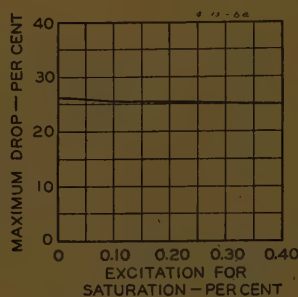
(b). Generator synchronous reactance, X_d



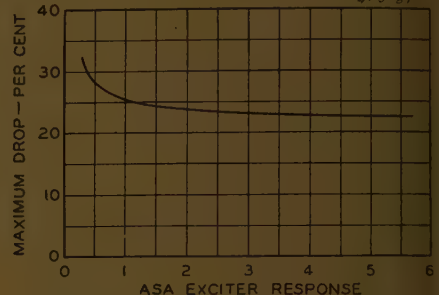
(c). Generator open-circuit time constant, T_{do}



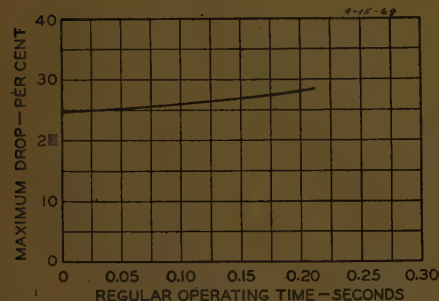
(d). Generator quadrature synchronous reactance, X_q



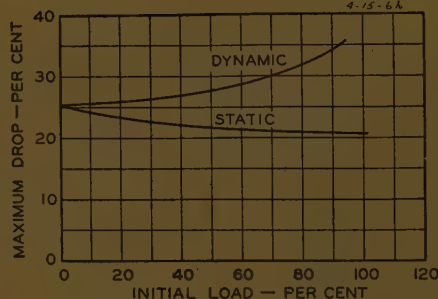
(e). Generator saturation, s



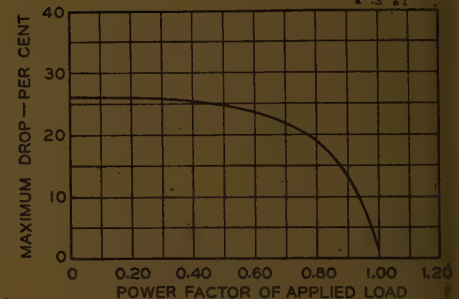
(f). Nominal exciter response, R



(g). Regulator operating time, h



(h). Type and amount of initial load, assumed at 0.80 power factor



(i). Power factor of applied load

An initial load is usually some combination of static and dynamic loads, and the voltage drop with additional suddenly applied load is therefore intermediate between the drop with an initial load entirely dynamic in character and the drop with entirely static initial load. Figure 6h indicates that the drop for such an average initial load condition is about the same as with no initial load; thus the curves of Figure 1, which were based on no initial load, apply with sufficient accuracy for most purposes where initial load is present, if such initial load is made up of a combination of static and dynamic load.

CHARACTERISTICS OF APPLIED LOAD

The curves of Figure 1 are based on a constant-impedance applied load, which as has been pointed out can be used to represent an induction motor during the starting period. In the curves the power factor of applied load was taken as 35 per cent, a typical motor-starting power factor. The maximum voltage drop is

Figure 6. Effect of various factors on maximum voltage drop when 100 per cent low-power-factor load is suddenly applied to an a-c generator

For each curve only the factor given as the abscissa was varied, other factors being kept constant at values given in Table II.

practically the same for all power factors from zero to 40 per cent but decreases rapidly for power factors above this figure, as indicated in Figure 6i.

Equations for Maximum Voltage Drop

In this section equations are derived into which machine and load quantities can be substituted to give directly the minimum voltage of the voltage-time curve of a generator under suddenly applied load. A simple mathematical expression for the build-up of voltage of a self-excited exciter is derived, based on the ASA definition of nominal response. This expression is substituted into the

differential equation of generator internal voltage under closed-circuited armature conditions, and the differential equation is solved, yielding an expression for the internal voltage as a function of time. An equation for the time at which the internal voltage is at its minimum value is derived. The time of minimum voltage, determined by means of the latter equation, can be substituted into the generator-voltage equation to determine the minimum internal voltage, from which the terminal voltage can readily be determined.

ANALYTICAL APPROXIMATION OF EXCITER BUILD-UP

The nominal response of an exciter is defined as the ratio to the nominal slip-ring voltage of the slope in volts per second of the straight line, beginning at nominal slip-ring voltage on the voltage-time curve and continuing for one-half second, under which the area is the same as the area under the actual no-load build-up curve over the same half-second in-

	Group 1	Group 2
Transient reactance, x_d' at.....	0.218 per unit	0.170 per unit
Synchronous reactance, x_d	0.932.....	0.715
Quadrature synchronous reactance, x_q	0.566.....	0.48
Open-circuit time constant T_{do}'	1.61 seconds	1.40 seconds
Excitation required for saturation at no-load normal voltage.....	0.183 per unit	0.312 per unit
Exciter response.....	2.16.....	2.77

interval. Nominal slip-ring voltage is the voltage required at the slip rings of the main generator to generate full load at rated power factor. An illustrative calculation of nominal exciter response is given in Figure 7.

The definition of nominal response suggests a means of approximating analytically the voltage-time curve of an exciter when the only information available about the exciter is its nominal response. In a self-excited exciter, terminal voltage builds up with an exponentially rising characteristic, following this characteristic until saturation limits it to a ceiling value. Over the unsaturated region of build-up, the voltage can be represented by an expression of the form

$$e_x = e_1 e^{t/T_e} \quad (1)$$

in which e_1 is the initial value of e_x , that is, the voltage at $t=0$, $e=2.718$, and T_e is a time constant depending upon exciter field and armature characteristics. Equation 1 can be used to represent the effect of an actual exciter by choosing the time constant T_e so that the resulting curve has the same nominal response as the actual exciter build-up curve. Such a curve, having the same nominal response, will then follow fairly closely the actual exciter curve over the half-second range beginning at nominal slip-ring voltage, and it can be used as a good approximation for voltages below nominal slip-ring voltage. Maximum voltage dip normally occurs with small and medium sized generators within one-quarter to one second after sudden application of load, and any departure of the analytical approximation from the actual curve within such times will be negligible. Use of the nominal response, which is based on the no-load build-up curve of the exciter, to represent exciter build-up under load conditions, is a justifiable approximation for usual exciter proportions. This will be shown later by comparison of tests with calculations involving this approximation.

The curve of Figure 8 gives directly values of T_e as a function of nominal response. The derivation of this curve is given in Appendix 1. Exciter build-up can be represented by substituting into equation 1 the value of T_e from Figure 8 corresponding to the response of the actual exciter. The initial exciter voltage, determined by the excitation requirements of the main generator under load conditions preceding sudden application of additional load, should be substituted for e_1 . Figure 7 gives a comparison of a typical exciter build-up curve with its analytical approximation, equation 1.

GENERATOR-FIELD-CIRCUIT EQUATION, ARMATURE OPEN-CIRCUITED

In the analysis of generator voltages and currents that follows, attention will be confined to effects in the main field and armature circuits, that is, subtransient currents in damper windings and pole faces will be neglected. The reason for this is that the time constant of decay of these subtransient effects is so short (on the order of two or three cycles) that their duration is negligible compared to the duration of the transient component. The transient time constants of normal machines and the time required for normal exciters to build up are so long by comparison that subtransient effects will have disappeared after a sudden change in the armature circuit long before the lowest point of the voltage dip is reached.

The differential equation for the field circuit of a generator with open-circuited armature is that for a simple series circuit with inductance and resistance:

$$L \frac{di_f}{dt} + ri_f = e_x \quad (2)$$

In equation 2, L is field-circuit inductance, i_f is field current, r is field resistance, and e_x is exciter voltage, fixed or variable. If this equation is divided through by r , and L/r is denoted by T_{do}' , the time constant of the field circuit when the armature is open-circuited, it can be written

$$T_{do}' \frac{di_f}{dt} + i_f = \frac{e_x}{r} \quad (3)$$

If i_f in equation 3 is expressed as a per-unit quantity in which one unit is the amount of field current required to produce unit voltage at no load on the air-gap line of the machine, it becomes identical with the per-unit value of e_d , the direct-axis synchronous internal voltage. That is, for each per-unit of value field current there is an equal per-unit

value of e_d . Likewise e_x/r can be expressed in per-unit terms where one unit is the field current required to produce unit voltage on the air-gap line. If one unit of e_x is taken as the exciter voltage required to force unit field current through the field resistance r , equation 3 can be rewritten in per-unit terms as follows:

$$T_{do}' \frac{de_d}{dt} + e_d = e_x \quad (4)$$

FIELD-CIRCUIT EQUATION WITH CLOSED-CIRCUITED ARMATURE

When a sudden change takes place in the armature circuit of a generator, nearly all the internal voltages of the machine, including e_d , undergo an instantaneous change. The one quantity that does not change instantaneously during a transition from one operating condition to another is e_d' , the direct-axis transient internal voltage. This quantity is proportional to the total flux linkages with the field winding, which cannot undergo an instantaneous change.

The fact that e_d' does not change during a transition makes it a convenient quantity to use in analyzing the effect of sudden load changes upon terminal voltage. The initial value of e_d' can be determined from the original operating conditions. This initial value can be used as a boundary condition in the solution of a differential equation for e_d' after a transition, and the resulting expression can be converted to terminal voltage by use of the new circuit constants.

Wagner¹ has given the relation between e_d and e_d' under closed-circuited armature conditions as

$$e_d = e_d' \frac{r_t^2 + x_{dt}x_{qt}}{r_t^2 + x_{dt}'x_{qt}} \quad (5)$$

In equation 5 the subscript t indicates the sum of a machine quantity and an external load quantity, that is

$$x_{dt}' = x_d' + x_{ext}$$

$$r_t = r_a + r_{ext}$$

and so on.

In modifying equation 4, which applies only when the armature is open-circuited, to get an expression for closed-circuit conditions, the change in the time constant T_{do}' caused by mutual effects between the armature and field circuits must be considered. Wagner has shown² that under closed-circuit conditions T_{do}' can be modified to give the equivalent closed-circuit time constant T_d' as follows:

$$T_d' = \frac{r_t^2 + x_{dt}'x_{qt}}{r_t^2 + x_{dt}x_{qt}} T_{do}' \quad (6)$$

Substituting the closed-circuit time constant T_d' for T_{do}' in equation 4 and substituting for e_d its value in terms of e_d' from equation 5, we get

$$T_{do}' \frac{de_d'}{dt} + \frac{T_{do}'}{T_d'} e_d' = e_x \quad (7)$$

which is the differential equation for e_d' under closed-circuited armature conditions.

SATURATION

In the derivation of equation 7 saturation was neglected and e_d was assumed to be equal under steady-state conditions to e_x . Equation 7 can be corrected for the effect of saturation by subtracting directly from e_x an amount of excitation corresponding to that used in overcoming saturation as the internal voltages of the machine vary.

In the graphical method of determining the voltage-time behavior of generators under suddenly applied load,¹ a step-by-step correction for saturation is made in the exciter voltage e_x as the voltage behind the Potier reactance of the generator varies. This correction, which is subtracted directly from e_x , is the per-unit amount of excitation required for saturation on the no-load saturation curve at voltages corresponding to instantaneous values of the Potier voltage e_p . Making the same correction in equation 7, calling the saturation component of excitation s and subtracting it from e_x we get

$$T_{do}' \frac{de_d'}{dt} + \frac{T_{do}'}{T_d'} e_d' = e_x - s \quad (8)$$

Calculation of a large number of specific cases using the graphical method indicates that over a wide range of conditions the correction s does not vary greatly from its value at no-load normal voltage. Analysis shows that this can be expected to occur for any normal range of machine constants and applied loads. For these reasons the saturation correction s has been assumed for convenience in solving equation 8 to be constant and equal to the per-unit amount of excitation required to overcome saturation at normal voltage no load. One unit of excitation, as previously noted, is the amount required to produce rated voltage on the air-gap line of the no-load saturation curve. Since the saturation correction s is a small quantity subtracted from the much larger quantity e_x , the error introduced by assuming s constant is small. The slight effect on the maximum voltage drop of varying the quantity s over a wide range is shown in Figure 6e, which further confirms the assumption that an average figure can be assumed for s without serious error.

GENERATOR VOLTAGE-TIME EQUATION

In Appendix 2, equation 8 is solved under the assumption of constant saturation, e_x being expressed in the form of equation 1. The resulting expression for the direct-axis transient internal voltage as a function of time is

$$e_d' = \left[\frac{e_1 T_d'^2 \epsilon^{\frac{h}{T_d'}}}{T_{do}'(T_e + T_d')} - \frac{(e_1 - s) T_d'}{T_{do}'} + e_{d1}' \right] \epsilon^{-\frac{t}{T_d'}} + \left[\frac{e_1 T_d' T_e}{T_{do}'(T_e + T_d')} \right] \epsilon^{\frac{t-h}{T_e}} - \frac{s T_d'}{T_{do}'} \quad (9)$$

in which e_1 is the initial exciter voltage in per unit, determined by the excitation requirements of the generator under load conditions preceding the load change; T_d' is the generator transient time constant in seconds, defined by equation 6; T_{do}' is the generator open-circuit time constant in seconds; T_e is the value read from Figure 8 corresponding to the response of the exciter; h is the equivalent regulator operating time; s is the per-unit excitation required for saturation at normal voltage on the no-load saturation curve of the generator; and e_{d1}' is the initial value of direct-axis transient internal voltage, calculated from the operating condition of the generator previous to the load change. For a generator initially operating at normal voltage, a per unit current i , and a power-factor angle ϕ , e_{d1}' in per unit will be

$$e_{d1}' = \frac{1 + (x_d' + x_q)i \sin \phi + x_q x_d' i^2}{\sqrt{1 + 2x_q i \sin \phi + x_q^2 i^2}} \quad (10)$$

For a machine operating initially at no load, $i=0$ and $e_{d1}'=1.0$. Equation 10 is derived in Appendix 3. The voltage e_d' given by equation 9 can be converted to terminal voltage e_t by the following expression.¹

$$e_t = \frac{\sqrt{(x_d'^2 + r_s^2)(x_{ext}^2 + r_{ext}^2)}}{x_{d1}' x_{q1} + r_s^2} e_d' \quad (11)$$

Most convenient use can be made of equation 9 in determining minimum e_t by substituting in it directly the value of t at which e_d' and e_t have their minimum values. By differentiating equation 9, setting the result equal to zero, and solving for t , it can be shown that the time at which these minimum values occur is

$$t = \frac{T_e T_d'}{0.434(T_e + T_d')} \log_{10} \left[\frac{e_1 T_d' \epsilon^{\frac{h}{T_d'}} - (e_1 - s - T_{do}' e_{d1}' / T_d')(T_e + T_d')}{e_1 T_d' \epsilon^{-\frac{t}{T_d'}} - \frac{s T_d'}{T_e}} \right] \quad (12)$$

By substituting t from equation 12 into equation 9 and applying equation 11, the minimum terminal voltage e_t can be determined directly.

Experimental Confirmation of Equations

The validity of the equations just derived has been checked by oscillographic tests. Two groups of tests were made, one on each of two complete generator, ex-

citer, and regulator setups. The combinations were in both cases identical in their essential parts to the setup shown in Figure 2.

In the first group of tests a large induction-motor starting load was applied to a 375-kva generator operating at various initial loads. The locked-rotor inrush of the motor at rated generator voltage was 363 kva, or 0.97 per unit of generator rating, at a power factor of 0.41. Exciter response was 2.16, and the operating time of the regulator was 0.05 second. Characteristics of the generator used in this group of tests are given in Table III.

A typical set of curves from an oscillogram made during this group of tests is shown in Figure 3. In this case the initial load on the generator was 0.20 per unit at unity power factor. Points from the voltage-dip curve calculated by means of equation 9 are shown for comparison. The calculated curve coincides closely with the test curve at minimum voltage and up to the time at which induction-motor speed approaches the maximum-torque point. The time of minimum voltage, determined by means of equation 12, coincides almost exactly with the actual time of minimum voltage from the oscillogram.

Figure 9 shows a representative test result from the second group of tests. In this group a 386-kva motor-starting load was applied to a 187-kva generator, an added load of 2.06 per unit. For the test shown in Figure 9, the generator was operating initially at no load. Agreement of the calculated points with test results is close up to the point at which motor impedance changes.

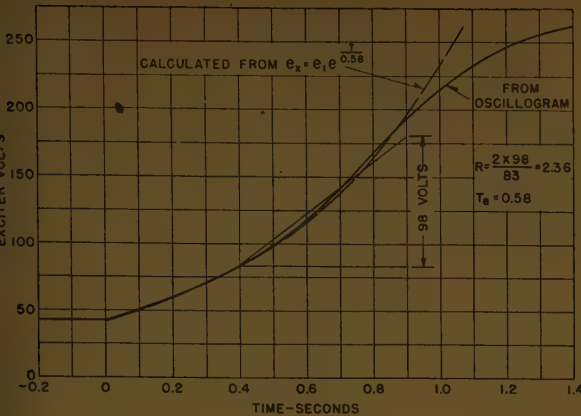
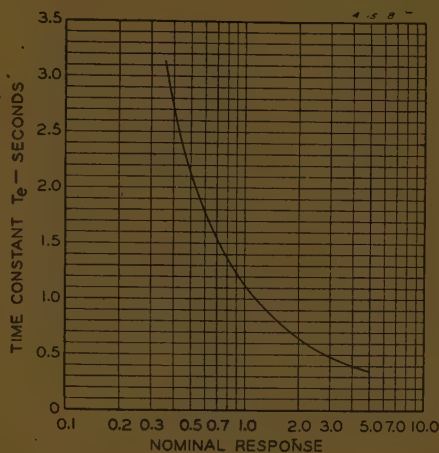


Figure 7. Voltage build-up curve of a self-excited exciter, showing method of calculating response

Nominal slip-ring voltage, 83 volts. Comparison of test curve with analytical approximation

Figure 8 (below). Time constant T_e for self-excited exciter versus nominal response



ops in other tests of these two groups as well as to several other generator setups indicates that the equations can be expected to give maximum voltage drops well within the accuracy limits usually required in engineering applications.

Conclusions

As a result of the studies described in this paper the following conclusions have been reached regarding the importance of various factors affecting voltage drop with suddenly applied low-power-factor load:

1. In the generator, the transient reactance and the open-circuit time constant are of prime importance. Reasonable variations in synchronous reactance have less effect. A method is presented of correcting for wide variations in synchronous reactance when using the voltage-drop curves. Variations in quadrature reactance and saturation have practically no effect on maximum drops.

2. For self-excited exciters the nominal response adequately expresses for practical cases the effect of exciter characteristics upon maximum voltage drops.

3. Regulator performance insofar as it affects maximum voltage drop is fully defined by the time required for the regulator to short-circuit the regulating resistance after a drop in voltage.

4. Depending upon whether it is static or dynamic in character, the initial load may reduce or increase the voltage drop slightly;

consequently, the assumption of no initial load gives a good representation of average initial load conditions.

5. Variations in the power factor of the applied load from zero to 40 per cent have a negligible effect on the maximum drop. This range includes normal starting power factors for squirrel-cage induction motors, so that the curves apply for usual motor-starting problems.

It has been generally concluded that maximum voltage drops can be expressed in terms of the four main parameters, generator transient reactance, generator open-circuit time constant, exciter response, and magnitude of suddenly applied load.

Mathematical expressions for generator voltage as a function of time have been

derived, based on the assumptions of constant generator saturation and the representation of exciter build-up as an exponential. These approximations are shown to be justified. The curves of voltage drop were calculated using these expressions.

Appendix I. Derivation of Curve of Exciter Time Constant T_e

From the definition of nominal response, the area in Figure 10 under the straight line between 0 and 0.5 second equals the area under the exciter build-up curve over the same period, and the slope of the straight line is the nominal response times the nominal slip-ring voltage, or Re_n . Under the assumption made in the text that exciter voltage rises exponentially, these relations can be expressed as follows:

$$\int_0^{0.5} e_n e^{t/T_e} dt = \frac{Re_n}{8} + \frac{e_n}{2} \quad (13)$$

Integrating equation 13 and solving for R , we get

$$R = 8T_e(e^{1/2T_e} - 1) - 4 \quad (14)$$

The curve of Figure 8 was plotted from the relation between R and T_e given by equation 14.

Appendix II. Solution of Differential Equation for e_d'

In the operational solution that follows, mathematical notation and the method of solution correspond to that used in reference 3. In this notation $H(t)$ represents the Heaviside unit function, and $H(t-h)$ represents the delayed unit function, that is, the function which is zero for t less than h and equal to unity for t greater than h .

The equation to be solved is equation 8. The quantity $e_x - s$ on the right-hand side must be expressed as a function of time. If the regulator operating time is called h , and if it assumed that the exciter build-up curve can be represented by the analytical approximation given by equation 1, the curve of exciter voltage after application of load will be as shown in Figure 11. The

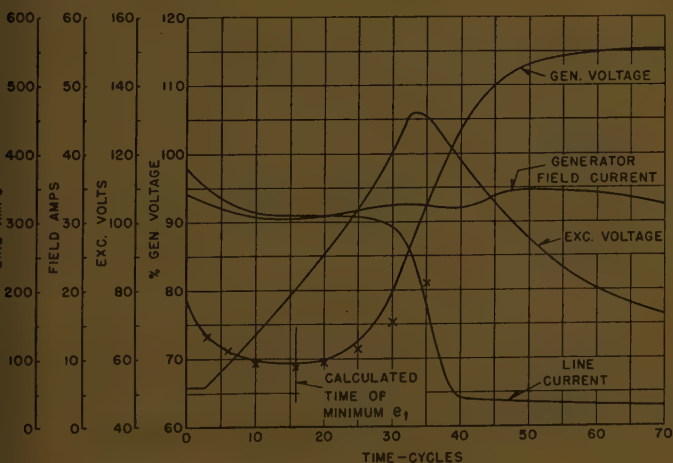


Figure 9. Comparison of calculated voltage-dip curve (crosses) with voltage-dip curve obtained from test

Added load 2.06 per unit at 0.40 power factor to 187-kva generator, operating initially at no load

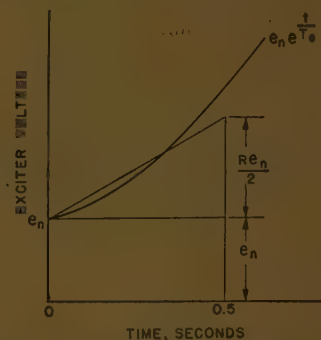


Figure 10. Derivation of relation between response and time constant T_e

Area under straight sloping line equals area under curve between 0 and 0.5 second

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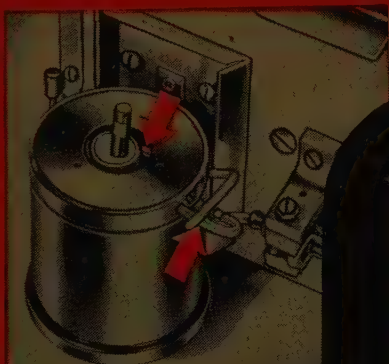
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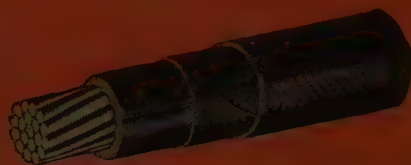
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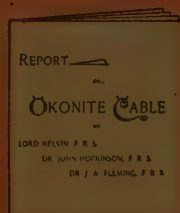
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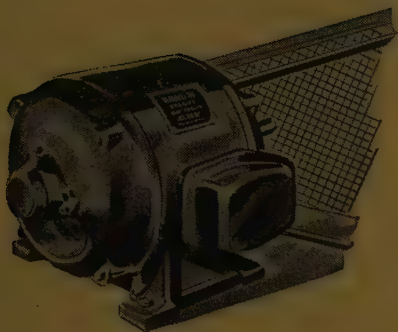
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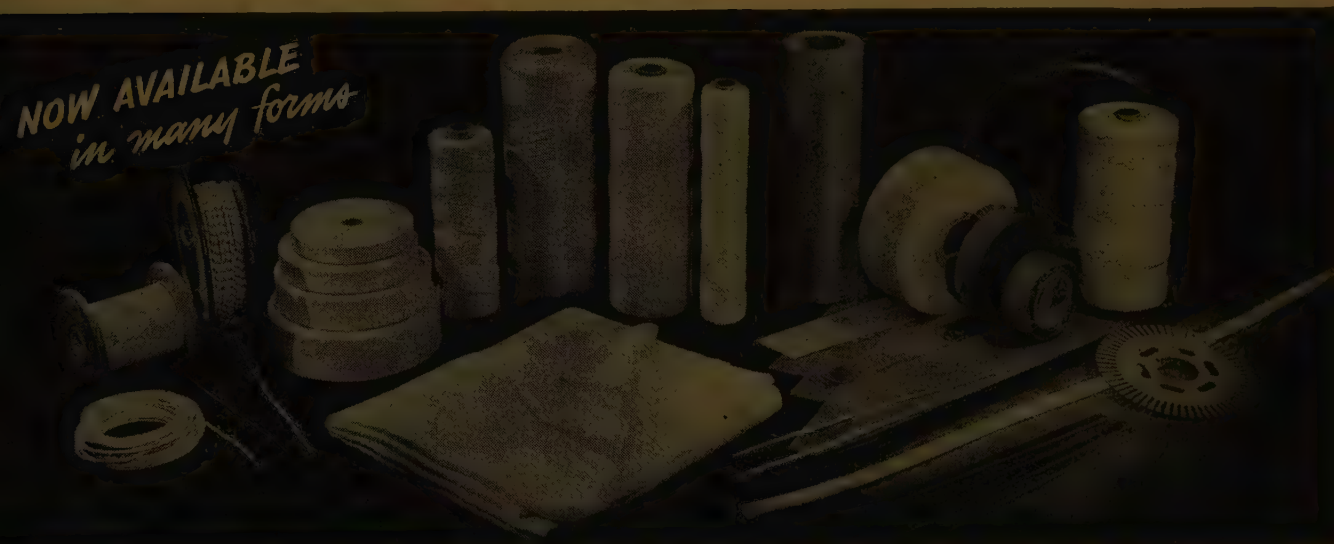
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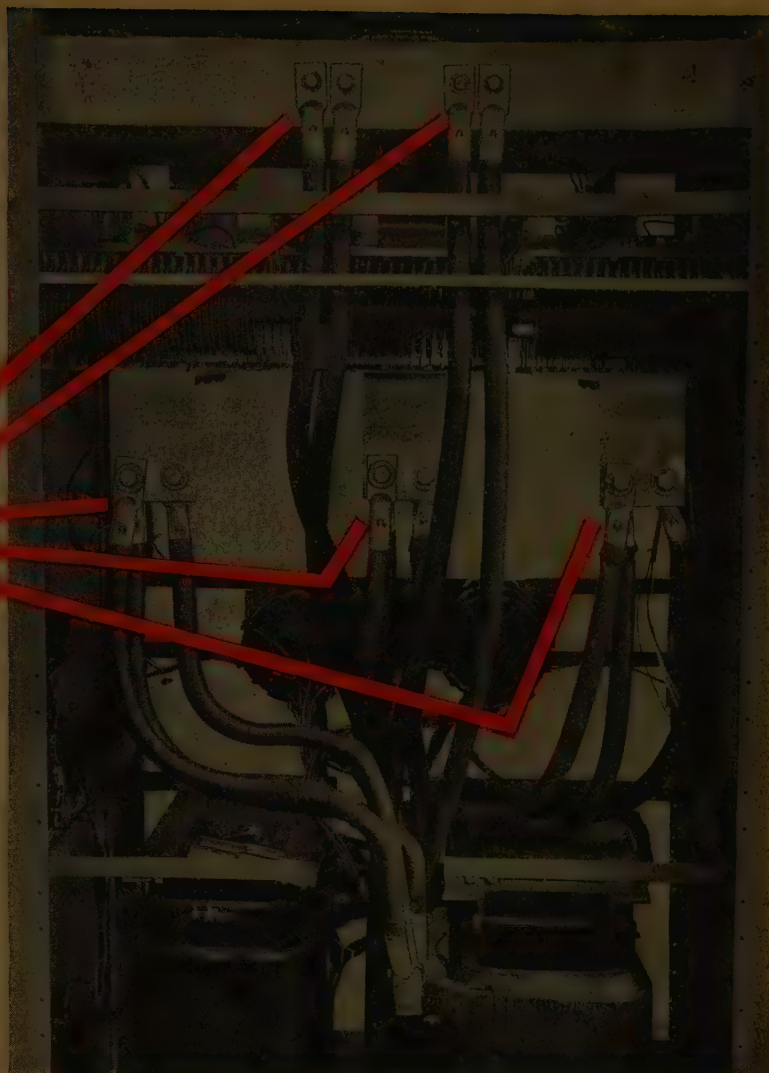
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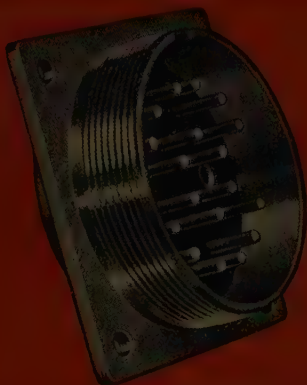


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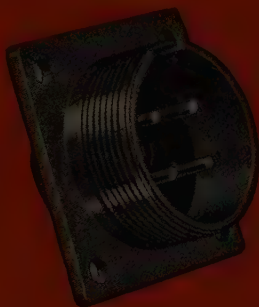


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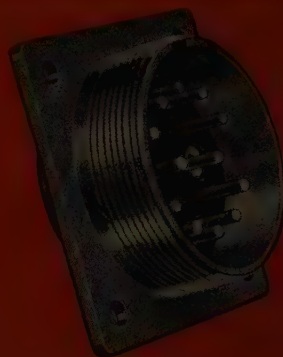
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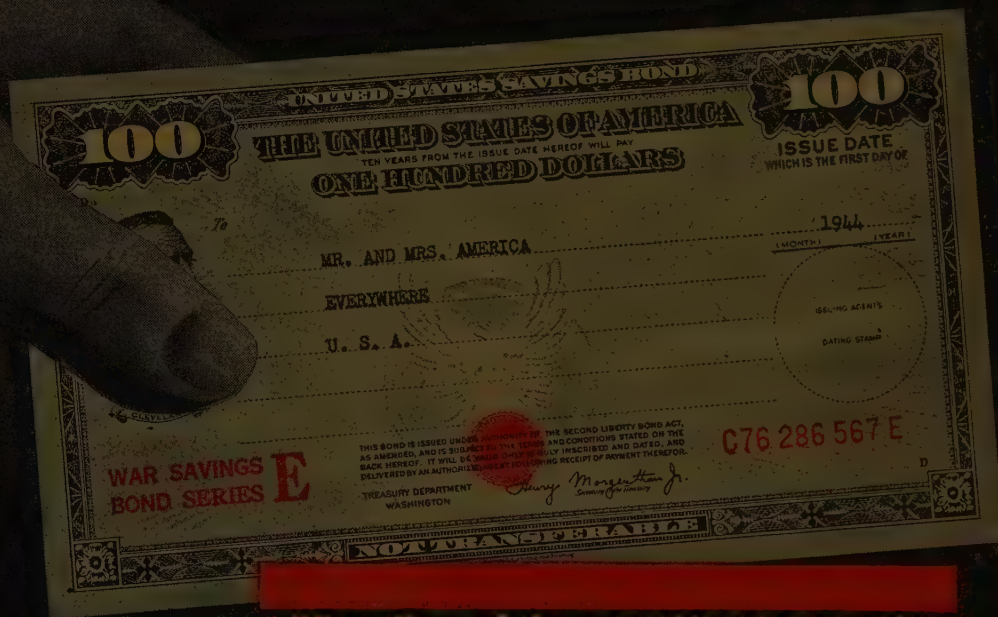


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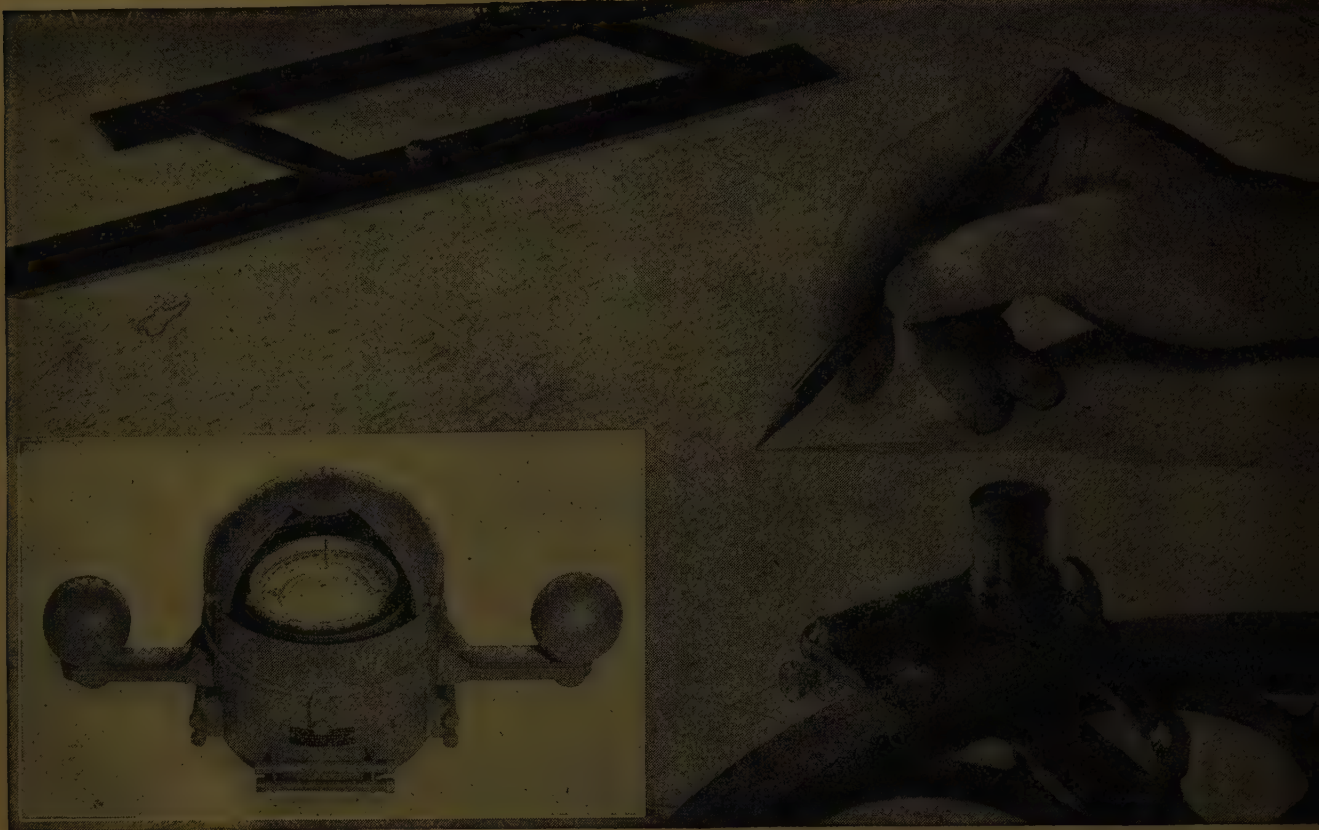
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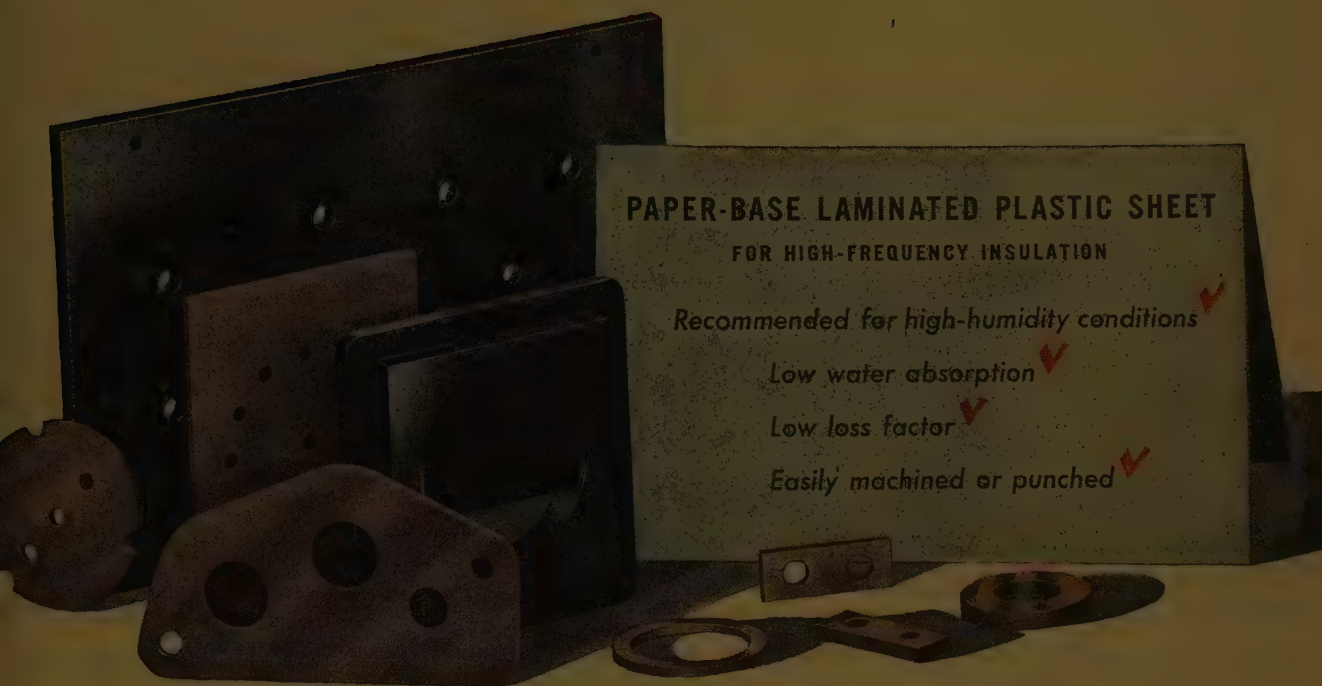
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Company

★ SPECIALISTS IN PERMANENT MAGNETS SINCE 1910 ★
6 NORTH MICHIGAN AVENUE • CHICAGO 2, ILLINOIS

BAKELITE

TRADE-MARK



PAPER-BASE LAMINATED PLASTIC SHEET FOR HIGH-FREQUENCY INSULATION

Recommended for high-humidity conditions ✓

Low water absorption ✓

Low loss factor ✓

Easily machined or punched ✓

FOR HIGH PERFORMANCE AT HIGH FREQUENCIES

Laminated Plastic Sheets made with BAKELITE Laminating Plastics

Increasing need for high-frequency equipment has called for vast increases in the production of paper-base laminated plastics known as XXX and XXXP grades. These plastics are made with a higher percentage of BAKELITE resins than other grades of laminates, providing much higher electrical values for the exacting demands of H.F. applications.

Type XXX, recommended for high-humidity conditions, possesses minimum cold-flow and excellent machining characteristics. Type XXXP has lower dielectric losses and is more suitable for hot punching work. It is also recommended for high-humidity applications. Its cold-flow is greater than that of the XXX

type. The loss factor of these materials is as low as .12 at 1,000,000 cycles (*A.S.T.M. D-150-39-T*); water absorption is as low as 1.0 per cent (*A.S.T.M. D-229-39*).

ASK YOUR LAMINATOR about the special grades of paper-base laminates for high-frequency use. If you have a problem involving an essential product, our field engineers and development laboratories are at your service. Or write for Booklet 5-L, "Bakelite Laminating Plastics."



BAKELITE CORPORATION, 30 East 42nd St., New York 17, N. Y.
Unit of Union Carbide and Carbon Corporation

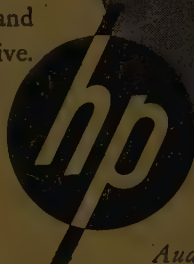


Laminating Plastics



INSTRUMENTS COVER A WIDE RANGE OF USES

Simplicity of operation combined with extreme accuracy makes for greater speed in measuring and testing AF apparatus. These fundamental characteristics are basically what makes *-hp-* instruments outstanding in the field. The variety of instruments available and the range of tests and measurements they accomplish is comprehensive. The following is a partial listing of standard *-hp-* instruments available at this time:



Audio frequency oscillators of the resistance-tuned type. Excellent frequency stability and freedom from wave form distortion. Model 200B Resistance-Tuned Oscillator illustrated.

Instruments for measuring frequency including secondary frequency standard and electronic frequency meters. Model 500A Electronic frequency Meter illustrated.

Instruments for measuring voltage in the audio and high frequency range. Model 400A Vacuum Tube Voltmeter illustrated.

Instruments for making over all measurements on audio equipment including total harmonic distortion, frequency response, and hum level. Model 325B Distortion Analyser illustrated.

Harmonic wave analysers with many new features including variable band width. Model 300A Wave Analyser illustrated.

Audio signal generators providing standardized voltage throughout the audio frequency range. Model 250AG Audio Signal Generator illustrated.

If you have a special problem *-hp-* Engineers will gladly cooperate without cost or obligation. Ask for Catalog number 17A and enter your name for regular receipt of technical bulletin.

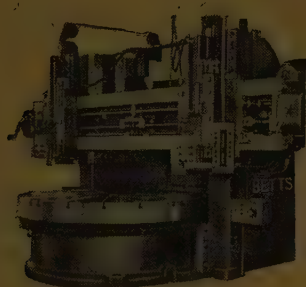
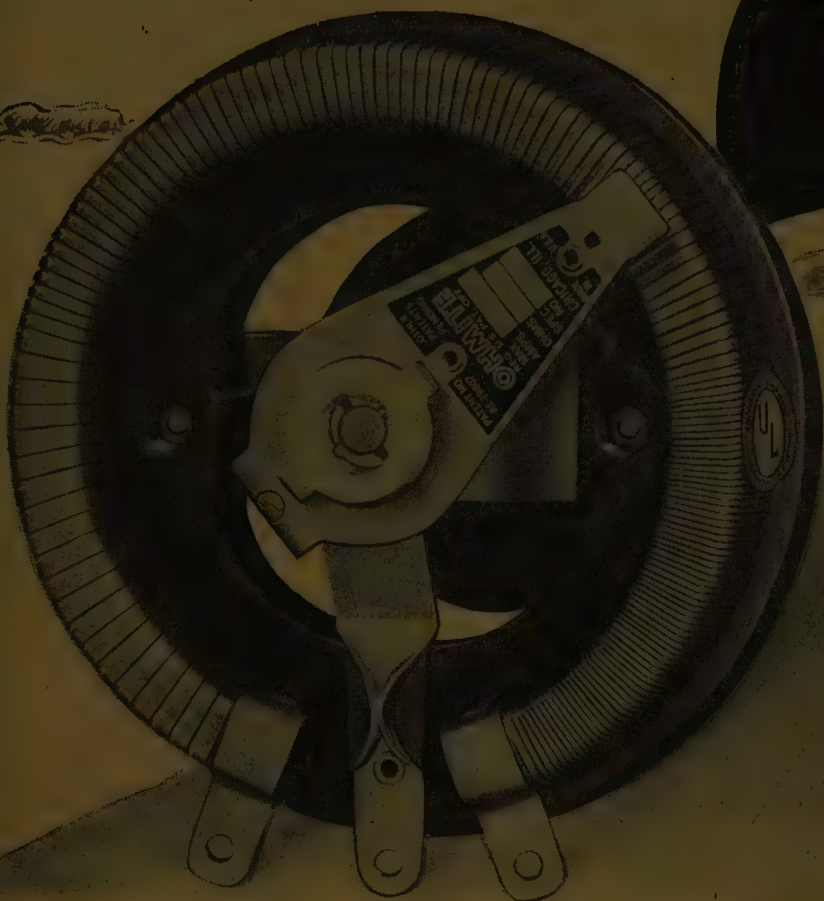
HEWLETT - PACKARD COMPANY

P. O. Box 876B • Station A • Palo Alto, California

OHMITE

RHEOSTATS

*Smooth, Close,
Continuously
Variable
Motor Speed
Control*



Used in Boring Mill Speed Control

A typical example is the use of two Ohmite taper-wound Model "R" Rheostats in the control system of this Boring Mill to help facilitate and speed up the machining of tank turrets.

Ohmite Rheostats are the "heart" of many of today's popular speed control systems for fractional horsepower and large power motors. Often, two rheostats in tandem are used to achieve both field and armature control.

This popular use of Ohmite Rheostats is logical—because: (1) they provide smooth, close, continuously variable control of a wide range of speeds; (2) they are compact—simple and convenient to use; (3) they have long life; there is nothing to shrink, shift or deteriorate.

Ohmite Rheostats are made in ten wattage sizes—from 25 to 1000 watts, from 1½" to 12" diameter—in straight or tapered winding—in single or tandem assemblies—in regular or special types.

OHMITE MANUFACTURING COMPANY
4803 FLOURNOY STREET, CHICAGO 44, ILLINOIS

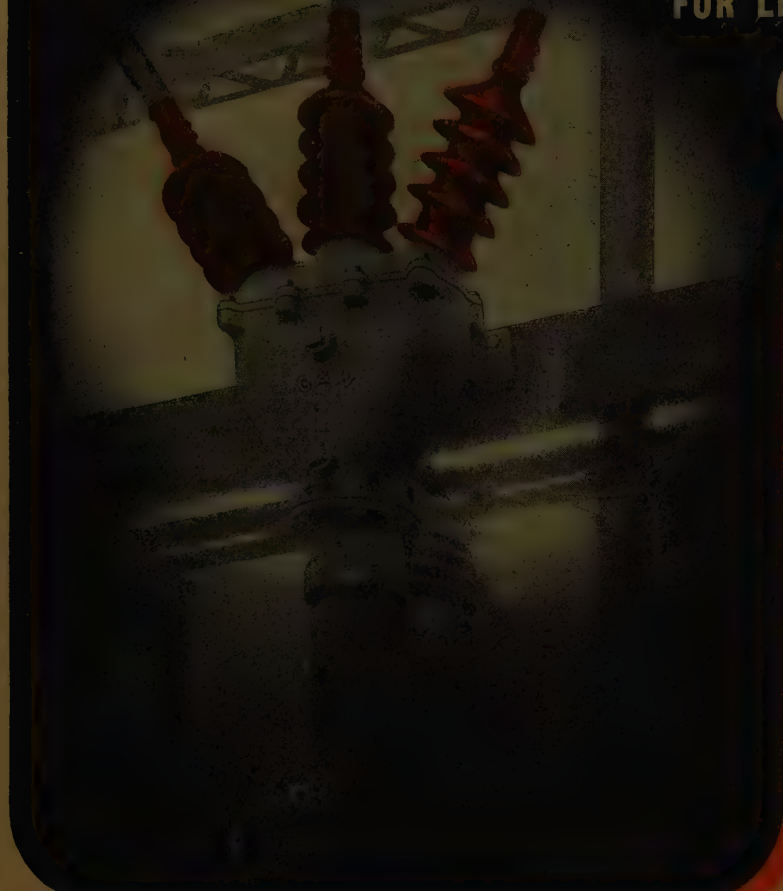
Send for Catalog and Engineering Manual No. 40. Write on company letterhead for this complete, helpful 96-page guide in the selection and application of Rheostats, Resistors, Tap Switches, Chokes and Attenuators.

Be Right with **OHMITE**
RHEOSTATS • RESISTORS • TAP SWITCHES

Here's POSITIVE PROTECTION

FOR LEAD SHEATHED CABLE ENDS

G & W POTHEADS

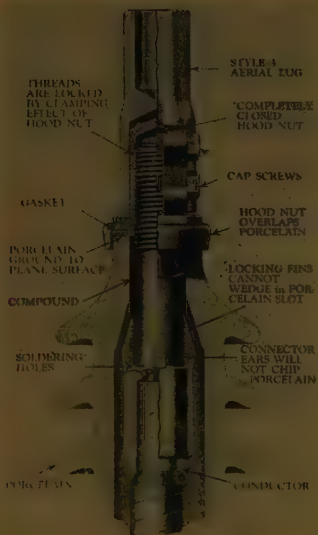


TYPE "T"

CAPNUT TERMINAL

The top of the porcelain insulator is the most vulnerable part of a pothead. G&W capnut construction provides a simple and positive seal at that point. The hoodnut completely encloses the threaded connector stem. The hoodnut flange compresses the gasket on the top end of the porcelain. The aerial lug clamps the hoodnut onto the connector stem so securely that the assembly will not loosen under vibration.

FOR A PERMANENT TIGHT SEAL AGAINST ENTRANCE OF MOISTURE OR LEAKAGE OF CABLE OIL, TIGHTEN THE HOODNUT WITH A LARGE WRENCH. YOU WILL NOT BREAK THE PORCELAIN BECAUSE IT IS UNDER COMPRESSION.



G & W ELECTRIC SPECIALTY CO.

7780 DANTE AVENUE

CHICAGO, ILLINOIS

In Canada—Powerlite Devices, Ltd., Toronto, Ont.

POTHEADS . . . BOXES . . . OIL FUSE CUTOUPS . . . OIL SWITCHES AND MULTIPLE CIRCUIT OIL DISCONNECTS



Rose-soft

*Write for Your
Complimentary Copy*

"I Shall Arise"—a portfolio
of Typhonite Eldorado pencil
productions by Samuel
Bamberlain. Subjects are build-
ings of art and historical impor-
tance bombed by the Luftwaffe.

The draftsman's skilled fingers revel in the rose-soft sensitiveness of Dixon's Typhonite Eldorado pencils. With every lead he draws with ease and sureness. No pencil distraction mars his satisfaction while he works with them, for Eldorado is the draftsman's drawing pencil.

TYPHONITE ELDORADO

PENCIL SALES DEPARTMENT 42-J6, JOSEPH DIXON CRUCIBLE COMPANY, JERSEY CITY 3, N.J.



VICTIMS OF A

"MECHANICAL BRAIN"

Zeros knocked out of the sky at the rate of one to every 90 rounds of ammunition fired! That's the feat our anti-aircraft batteries are performing in the South Pacific. During World War I, the average was but one plane to every 17,000 rounds.

Credit is due largely to the new M9 gun director—a "mechanical brain" that aims a battery of four 90mm. guns and sets their fuses. Everything is done mathematically by electricity.

The delicate synchronization of tracker, height finder, computer, power rectifier and altitude converter depends on scientific perfection of the electrical cable.

Laytex Portable Cable, developed by U.S. Rubber Company engineers, is used throughout. It transmits the data for lightning-fast calculation without chance of human error, resulting in fire control of deadly accuracy. Results attest how exactly this cable meets this specialized need.

Laytex
REG. U. S. PAT. OFF.

WIRES AND CABLES



SERVING THROUGH SCIENCE



PURIFIED LIQUID LATEX is used for Laytex Wire and Cable Insulation. A special process removes moisture and water-soluble impurities. Laytex insulation—whether made from either natural or synthetic rubber—has exceptional dielectric strength.



CABLE AND PLUG ASSEMBLY for the M9 gun director. Laytex Insulation developed by U.S. Rubber Company engineers is built up into a homogeneous unit around the perfectly centered wires by an exclusive process of repeated dipping and drying, followed by vulcanization.

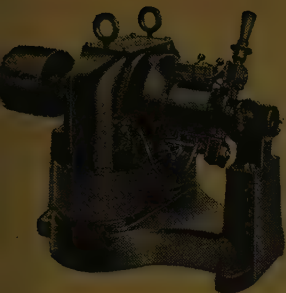


TOMORROW'S PROMISE — Although the entire output is still going to meet critical war needs, a day will inevitably arrive when we shall again supply U. S. Laytex Wires and Cables for Buildings, Police and Fire Alarms, Communications, Signalling, Power and Control.

Listen to the Philharmonic-Symphony program over the CBS network Sunday afternoon, 3:00 to 4:30 E.W.T. Carl Van Doren and a guest star present an interlude of historical significance.

UNITED STATES RUBBER COMPANY

1230 SIXTH AVENUE, ROCKEFELLER CENTER, NEW YORK 20, N. Y. • In Canada: DOMINION RUBBER CO., LTD.



Serial No. 1 . . . Crocker-Wheeler Motor, built in 1888.



Serial No. 1,000,000 . . . SEALEDPower
(Cowl-Cooled) Motor . . . for all polyphase alternating current circuits, 2 to 15 horsepower.

SEALEDPower

Industry's Most Trouble-Free Motor

PRODUCED BY CROCKER-WHEELER'S 56 YEARS OF EXPERIENCE

CROCKER-WHEELER FEATURES:

1. Patented "Groovseal"—no greasing needed for at least a year. Grooves minimize grease loss. This seal makes bearing maintenance expense negligible. It permits use of softer grease, for better lubrication and longer bearing life. Airtight seal prevents dust or other foreign matter from entering bearings.

2. Crocker-Wheeler's exclusive De-Sludging Impeller. Automatically desludges . . . churns and distributes grease to bearings when motor is started.

3. Vacuum Impregnation—standard on all Crocker-Wheeler motors. Seals out foreign matter and moisture from each individual coil . . . fills all interstices, making windings a homogeneous mass . . . reduces

hot-spot temperature and lengthens insulation life. Adherence of varnish prevents vibration of wires either inside or outside of slot. (Photograph shows cross sections of baseballs, (left) after vacuum impregnation and (right) before vacuum impregnation. Note penetration of varnish to center of tightly-wound ball, making it a moisture-proof, homogeneous mass.)

SEALEDPower FEATURES:

4. Totally Enclosed Cowl-Cooled Construction resists corrosion. Protects against acid or alkali fumes, splashing or dripping liquids, air-borne moisture, steam, corrosive gases, conducting dusts, metallic chips, etc.

5. Fin Type Construction for non-clog ventilation and easy cleaning.

WRITE FOR LITERATURE ON THE SEALEDPower MOTOR, WHICH IS WINNING THE PREFERENCE OF MACHINERY MANUFACTURERS AS WELL AS OF MOTOR USERS. OR CALL OUR NEAREST OFFICE.

JOSHUA HENDY IRON WORKS

CROCKER-WHEELER DIVISION

ESTABLISHED 1856

AMPERE, NEW JERSEY

Branch Offices: BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND • DETROIT • NEW YORK • PHILADELPHIA • PITTSBURGH • SAN FRANCISCO • WASHINGTON • LOS ANGELES



SQUIRREL CAGE MOTORS

WOUND ROTOR MOTORS

DIRECT CURRENT MOTORS

GENERATORS

FLEXIBLE COUPLINGS

Styles have changed since 1909,
the year the first ACSR was made



First Aluminum Cable Steel Reinforced

Line styles have changed, but the ACSR of this
country has followed the original formula, and the
strength, economy, versatility and long life.



The first Aluminum Cable Steel Reinforced was fabricated in 1909 by Aluminum Company of America. Its size was No. 2 (No. 4 copper equivalent); a conductor now widely used in rural electrification. Six aluminum wires are stranded around one steel wire, to give a combination of high electrical conductivity, durability and high strength.

Line styles have changed considerably since then. Structures, insulators and fittings have all put on new faces. Spans have been greatly lengthened to reduce construction costs, permitting extension of service into low income

areas. The advantages which gave the ACSR of 1909 acceptance by line builders have made it equally popular for these modern rural lines.

Thousands of miles of ACSR have been purchased for the construction and extension of rural lines. Builders have had the counsel of Alcoa's engineers and supervisors, receiving recommendations based on experience gained during these many years, 1909 to 1944.

This service is available to help you keep war-loaded lines on the job, or extend them into new areas. ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh 19, Penna.

ALCOA RESEARCH GIVES YOU



PROVED STANDARDS FOR
LINE CONSTRUCTION

ALCOA A-C-S-R

ALUMINUM CABLE STEEL REINFORCED





O-B LINE POSTS NEVER CHANGE

BECAUSE THEIR VITAL INNER CHAMBER IS SEALED IN CHANGELESS PORCELAIN

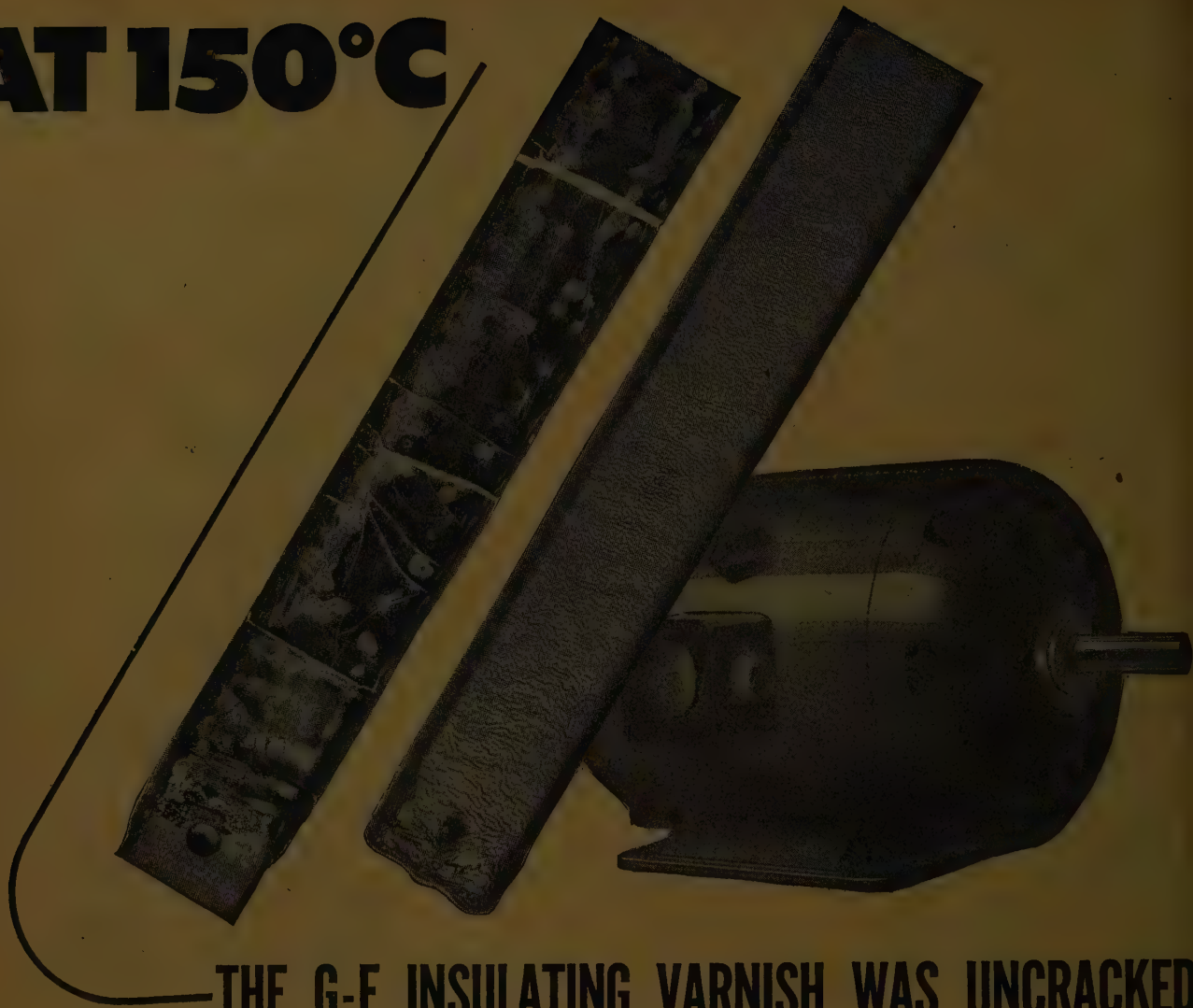
Post type insulators are just as good as their seal--and no better! Any moisture that can ever be drawn into the inner chamber will result in serious deterioration of a unit's dielectric and radio values...In the O-B line post, this seal is proved for its soundness by a prolonged vacuum holding test and its permanence is assured by use of a glazed-in porcelain barrier. Time, temperature, or any other operating condition can have no effect on the O-B ceramic seal...If your design requirements call for post insulators, specify O-B Line Posts whose all-porcelain construction makes their original electrical characteristics lasting and un-changeable as porcelain itself.



Ohio Brass
MANSFIELD, OHIO, U.S.A.
CANADIAN OHIO BRASS CO., LTD.,
NIAGARA FALLS, ONTARIO

2472-H

AT 150°C



THE G-E INSULATING VARNISH WAS UNCRACKED

THERE IS A G-E INSULATING VARNISH FOR EVERY NEED

★

Hear the General Electric radio programs: The G-E "All Girl Orchestra" Sunday 10 p.m., EWT, NBC; "The World Today" news every weekday 6:45 p.m., EWT, CBS.

BUY WAR BONDS

Rigid tests of each new varnish developed by General Electric is a prime prerequisite to placing it on the market. And, naturally, these tests are made under conditions duplicating, in a more exacting degree, those which the varnish is compounded to meet. Typical was the test of two varnishes, each intended for insulating electrical apparatus where high temperatures would be encountered. The G-E varnish withstood the accelerated heat-aging test; the other broke down.

If you face a problem in finding the correct insulating varnish for your specific needs, the engineering staff of the Resin and Insulation Materials Division of the General Electric Company will gladly cooperate with you. Consult your local G-E Distributor or write to Section M543-12, General Electric Company, Schenectady 5, New York. (Varnishes are one product in the complete line of G-E insulation materials).

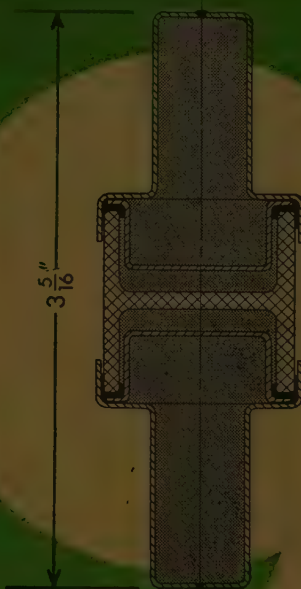
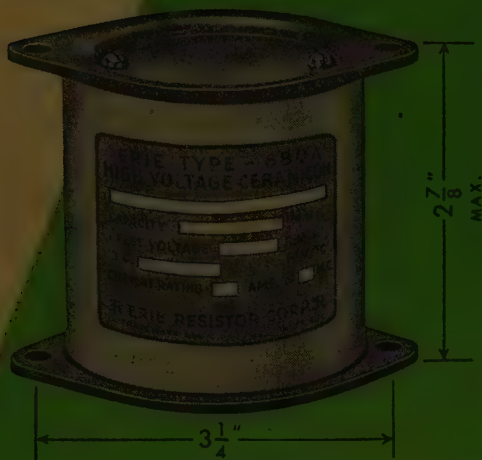
GENERAL ELECTRIC

Ceramicon Designs

REG. U. S. PAT. OFF.



FOR RADIO FREQUENCY AND
HIGH **KVA** APPLICATIONS



PIONEERED BY *Erie Resistor*

THE two condensers illustrated above are examples of two basic ceramic condenser designs developed by Erie Resistor for high voltage, high KVA applications.

Shown at the left is the Erie Type 680A transmitting condenser that is designed for 6000 volts RMS test voltage. This unit consists essentially of a number of silvered ceramic discs, each having the well known stability and temperature retrace characteristics of compensating Ceramicons, and in addition are designed to safely withstand high voltages required in this type of condenser.

The Antenna Coupling Ceramicon illustrated at the right employs the double cup design originated by Erie Resistor. In developing this unit Erie engineers successfully overcame the problems of eliminating corona and dissipating internal heat while retaining small size and simplicity of design. The specifications of this condenser, given at the right, show the high degree of perfection it has now reached.

Erie Resistor is working further on the development of similar Ceramicon designs for other applications. If you have a condenser problem connected with present day

equipment, or for postwar applications involving high voltage, high KVA units, we would like to discuss Erie Ceramicons with you. Our wide experience, beginning in 1935 with the first development of ceramic condensers in this country, gives us a comprehensive background on which to base recommendations.

CHARACTERISTICS

Left: Type 680A Transmitting Ceramicon Maximum capacity 400 MMF in zero temperature coefficient, 2000 MMF in -750 P/M/°C. 10,000 volts D. C. test voltage.

Right: Erie Antenna Coupling Condenser: Maximum capacity 50 MMF in zero, 250 MMF in -750 P/M/°C temperature coefficient. Typical rating in zero coefficient, maximum R.F. current 3 amps at 3 MC and 5 amps at 9 MC at 65°C. Test voltage 6000 volts D. C.



FOR HIGH ACHIEVEMENT
OUTWARD PROGRESS

Back The Attack—With War Bonds

ERIE RESISTOR CORP., ERIE, PA. LONDON, ENGLAND, TORONTO, CANADA



... Good
CARRIER.



69 kv
0.003 muf



115 kv
0.002 muf



138 kv
0.0015 muf



161 kv
0.0012 muf



230 kv
0.001 muf



287 kv
0.00075 muf

This "family" of standardized G-E Type CW carrier-current coupling capacitors and Type KA potential devices permits assemblies of any established voltage ratings.

GENERAL  **ELECTRIC**

Coupling for better CARRIER CURRENT SERVICE

COUPLING capacitors are the bridge between carrier equipment and the power line. They couple two fields of engineering—electric power and electronics. Joint use of lines for carrier current and power requires coupling capacitor units capable of withstanding the highest transmission line voltages and of passing the lowest carrier-frequency voltage.

G-E engineers have pioneered almost every outstanding achievement in carrier-current development. In G-E Type CW coupling capacitors they have developed coupling of extraordinary structural and electrical dependability. This coupling faithfully passes one or more carrier frequencies—regardless of lightning, line-switching surges, rain, snow and sleet. It also has permitted many existing carrier-current installations to take on extra-heavy war duties. When combined with G-E potential devices, this coupling greatly reduces the size, weight and cost of critical materials necessary to provide potential for synchronizing, relaying, and similar services.

In the past ten years, more than 8000 G-E CW capacitor units have been applied to new carrier-current installations, and modernization

of old ones—*without a single electrical failure.*

General Electric engineers are prepared to discuss—*now*—the carrier-current services and equipment which may be advantageously applied to your particular light-and-power system—either toward immediate operating improvements or as a part of your expansion program. *General Electric, Schenectady, N. Y.*

• Tune in "The World Today" every evening except Sunday at 6:45 E.W.T. over CBS. On Sunday listen to the G-E "All Girl Orchestra" at 10 P. M. E.W.T. over NBC.

ANY COMBINATION OF CARRIER-CURRENT SERVICES YOU NEED

may be made from 77 different G-E standard "Panel Units"—housed in standard cabinets of convenient size for indoor or outdoor installation. Major carrier functions include: *Pilot Relaying, Transferred Tripping, Signaling, Telephony, Telemetering, Supervisory Control, Automatic Load Control, Line Sectionalizing Control.*

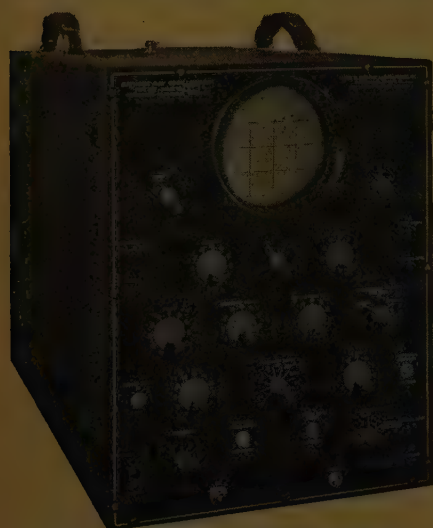


GENERAL ELECTRIC HAS PLANNED AND
BUILT MORE CARRIER-CURRENT
EQUIPMENT THAN ALL OTHER
MANUFACTURERS COMBINED

CARRIER CURRENT

THE NERVE NETWORK OF THE POWER SYSTEM

Another



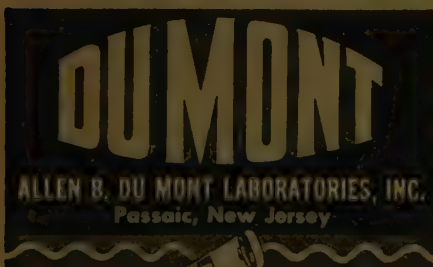
DUMONT Contribution

● This latest oscillograph facilitates the investigation of transient as well as recurrent phenomena over a wide frequency range. And since a permanent record of transient phenomena is usually desirable, this instrument provides for such photographic recording by applying comparatively high accelerating potentials to its cathode-ray tube. Furthermore, a new type of beam-control circuit is incorporated.

The sweep frequency range has been extended. The instrument may be used for observations on low-speed machinery and for other low-frequency signal functions—even down to $\frac{1}{2}$ cycle per second. At the other extreme, the instrument handles radio-frequency signals as high as 500 kilocycles. The time-base has the necessary range to display such signals properly. Also, the vertical amplifier can satisfactorily accommodate them.

● Write for Literature . . .

This oscillograph may meet your particular requirements. If not, there are other DuMont oscillographs with other characteristics that may meet your needs. You'll find them listed and described in our manual—copy on request.



Cable Address: Wespexlin, New York

IMPERIAL NEOPRENE JACKETED PORTABLE CABLES

The CRESCENT NATION WIDE ORGANIZATION



originating at this factory at Trenton, N. J., serves the nation from coast to coast. Wherever you are located, these Representatives stand ready to assist you:

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Dallas, Texas
N. Y. City 18, N. Y.
*Los Angeles 54, Cal.
*Boston 10, Mass.
San Juan, P. R.
* Warehouse



CRESCENT INSULATED WIRE & CABLE CO.

TRENTON, N. J.



CRESCENT

WIRE and CABLE

● RUBBER POWER CABLES ● VARNISHED CAMBRIC CABLES

CHALLENGE!

As you look through the ads in this magazine...

FIND THE GLASS PARTS NOT MADE AT CORNING

IT'S really not much of a gamble on our part. The truth is that most of the electronic glass equipment built today comes from Corning Glass Works.

Bulbs, flares, insulators, transformer bushings, tubing, resistor tubes, coil forms, are just a few of the hundreds of electronic glassware products produced under our Army-Navy "E" flag. Here you will find glasses with high electrical insulating qualities; glasses with an expansion coefficient practically equal to that of fused quartz; glasses extremely resistant to mechanical shock; glasses that can now be made into intricate shapes formerly considered impossible. And be-

hind them all, 75 years of pioneering in glass research and experience gained in the development of more than 25,000 glass formulae.

We hope this doesn't scare you. All it means is this: If you have a problem you think glass might be helpful in solving, feel free to call on Corning! Everything we know about glass is at your service. Just to get started we'd like to send you a copy of an informative new booklet, "There Will Be More Glass Parts In Post-war Electrical Products." If interested, write Electronic Sales Dept. N-6, Bulb and Tubing Division, Corning GlassWorks, Corning, New York.



CORNING
means
Research in Glass

Electronic Glassware



"PYREX" and "CORNING" are registered trade-marks of Corning Glass Works

IRC WILL BE READY

with SEALED PRECISION VOLTMETER MULTIPLIERS



When "that day" arrives, I R C will be able to supply not only voltmeter multipliers but *all* types of resistances, to meet industry's peace-time needs.

There will be no lag because of reconversion. Instead, the vast quantities of resistors being turned out for the Armed Services can be immediately diverted to civilian goods channels at prices consistent with the mass production methods now in effect.

Meanwhile, members of our engineering staff will be glad to consult with any manufacturers whose post-war plans involve resistance units. There is no obligation, and of course you can be certain all information will be held in confidence.

FEATURES OF SEALED PRECISION VOLTMETER MULTIPLIERS

1. Meet all test requirements of A.S.A. Standard C-75.5-1943.
2. Space and layer wound with enamelled wire and with silver soldered connections.
3. Sealed to withstand all salt atmospheric and tropical conditions.
4. Non-inductively wound to one half of one percent.
5. Extra safety factor through the use of large diameter wire and special insulation against voltage breakdown.



INTERNATIONAL RESISTANCE CO.

401 N. Broad St. Philadelphia 8, Pa.

IRC makes more types of resistance units, in more shapes, for more applications than any other manufacturer in the world.



MORGANITE BRUSHES



When a machine constructor chooses a grade of brush for a given motor or generator, he wants to know that the material is uniform and can be uniformly reproduced over a period of years.

In service also, operating and maintenance men want brushes that give identical results when replacements are required.

Through the years, Morganite brushes have remained uniform within close limits. Because constructors and operators know they can depend on Morganite brushes, you will find them on many heavy duty machines.

When a brush problem arises, communicate with Morganite and obtain an honest helpful answer.

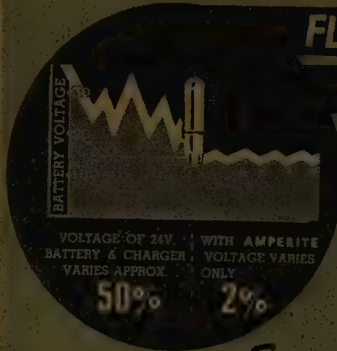
MORGANITE BRUSH COMPANY, Inc.
Long Island City 1, New York



No. 5 in a Series of Factors Essential to Maximum Brush Efficiency

... uniformity
of material
necessary for
continued
brush satisfaction

CURRENT and VOLTAGE FLUCTUATION REDUCED



WITH
**AMPERITE
REGULATORS**

Features:

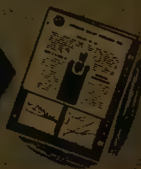
1. Amperites cut battery voltage fluctuation from approximately 50% to 2%.
2. Hermetically sealed — not affected by altitude, ambient temperature, humidity.
3. Compact, light, and inexpensive.

Used by U.S. Army, Navy, and Air Corps.

DELAY RELAYS: For delays from 1 to 100 seconds.
Hermetically sealed. Unaffected by altitude. Send for catalogue sheet.

ENGINEERS: This 32-page folder will help you solve many valuable data in practical form — Write for your copy now.

AMPERITE CO., 561 Broadway, New York (12), N. Y.
In Canada: Atlas Radio Corp., Ltd., 580 King St., W. Toronto



Non-inductive paper sections in heavy tubing.

Extra-wax-sealed against moisture penetration.

Bare pigtail lead terminals will not work loose.

Victory Line, readily available, contains 8 different capacity values to meet usual requirements. 600 volt ratings.

• Yes, millions of these Aerovox paper tubular capacitors are proving their worth, day after day, in radio, electronic and other equipment. They cost relatively little. Yet they are made with scrupulous care and great skill. Finally, each and every one is individually tested.

• Write for latest catalog covering an outstanding line of capacitors for all requirements.



Capacitors
INDIVIDUALLY TESTED

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MR. LITTLE and MR. BIG

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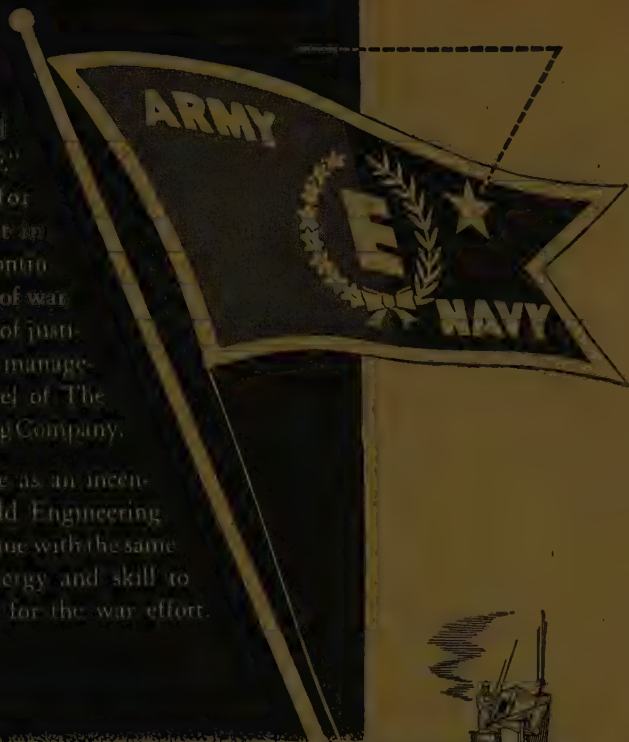


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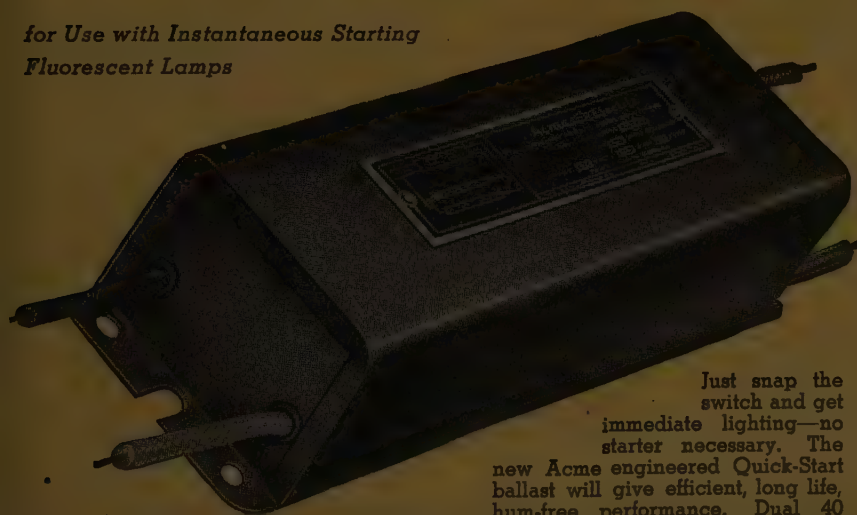
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- (3) BROAD, UNIFORM COMMUTATING SURFACE results from grinding commutator track on the parallel, uniformly spaced wires of the outside, cylindrical portion of the coil.

(4) SMOOTH, COMMUTATING SURFACE: no bumps jar the brush to cause breakage or arcing.

(5) LONGER BRUSH provides sturdiness, larger heat dissipating surface, and a greater contact area that reduces the current density per square inch of brush contact.

(6) BALANCED COLLECTOR ARM maintains brush setting when mounted in any position.

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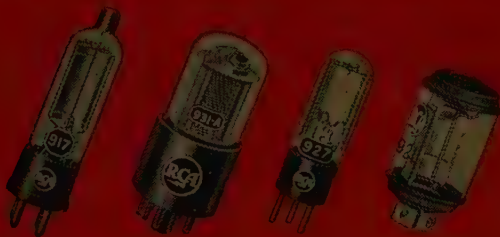
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HOW TO SELECT PHOTOTUBES



Characteristic	High-Vacuum type	Gas-filled type	Multiplier type
Sensitivity	Low	Medium	Very high
Current Output	Low	Medium	Very high
Amplification factor	1	Up to 10	Up to 1,000,000
Relative signal-to-noise ratio (including amplifier stage)	Low	Intermediate	High
Anode Volts	Up to 500	Not over 90	Up to 1250
Distortion (audio)	Negligible	Appreciable in some cases	Negligible
Frequency Range	Limited largely by circuit	Limited by tube performance	Limited largely by circuit

Gas-filled phototubes are, at present, extensively used for sound-on-film reproduction and for relay work. Vacuum-types are widely used where high sensitivity is needed; for precision measurements where stability of calibration is essential; and for high-speed work.

Sensitivity: The sensitivity of a phototube may vary according to whether the light change is abrupt or continuous. *Static sensitivity* is the ratio of anode direct current to constant light flux. *Dynamic sensitivity* is the ratio of the variation of anode current to the variation of light input. The sensitivity of gas-filled phototubes drops off as light-source frequency increases.

Optical Systems: The use of phototubes usually involves some sort of optical system. The fundamentals of optics must be carefully considered in the successful application of phototubes.

Mechanical Features: As illustrated at left, several types of tubes are available. Size, vibration, directional requirements, etc., may influence the choice of one of the many RCA phototubes.

Phototube Life: Phototubes are inherently sturdy, long-lived tubes and when operated under recommended conditions, give extended reliable service.

Application Hints: Here are a few general suggestions on applying phototubes:

1. In relay and measurement circuits where tubes must respond to very small amounts of light, avoid leakage currents outside tube. Keep tube terminals and sockets clean. Erratic leakage currents will affect results.
2. In amplifiers where low leakage is important, select top quality types such as 917, 919, or 935.
3. Shield phototube and leads to amplifier or relay tubes where amplifier gain or phototube load resistance is high.
4. Where high-frequency response is important keep phototube leads short to minimize capacitance shunting of output.
5. For constant calibration of high-precision vacuum phototube devices, keep anode voltage at or below 20 volts. Keep incident light spread over wide cathode area.
6. Design or circuit constants should be based on tests with the equipment operating over the expected range of line-voltage variation.
7. RCA voltage-regulator tubes can improve phototube circuit performance.
8. Anode characteristic curves on phototubes can be used to predict performance under given operating conditions.

PHOTOTUBES have found such a wide variety of applications that many types have been developed to meet special needs. The complete RCA line includes both gas-filled and high-vacuum phototubes, with various spectral responses and a variety of sizes and shapes. And for applications requiring extreme sensitivity, RCA supplies multiplier phototubes.

A phototube acts as a light-actuated electric valve. (It does not convert light energy to electrical energy, but acts only as a control device.) The current passed is in proportion to incident light. Some phototubes are "high-vacuum" types; some are filled with an inert gas (such as argon) to increase current-carrying capacity. A multiplier phototube contains additional electrodes (dynodes) which emit secondary electrons and thus greatly increase sensitivity and output current as compared to 2-electrode phototubes.

Color Sensitivity: The cathode coating material and the envelope glass determine color sensitivity. RCA phototubes fall into five "color groups":

Use	Tube Types	Maximum Color Sensitivity
With incandescent lamps	High vacuum: 925, Gas-filled: 868, 920, 924, 927*, 928	Red and infra-red
With incandescent lamps and for infra-red application	High vacuum: 917, 919, 922*, Gas-filled: 918, 921*, 923, 930*	Similar to above, but sensitivity extended further into infra-red
With light source for colorimetry application	High-vacuum: 926	Blue light. Approximates the human eye
With daylight, carbon-arc, or mercury-vapor light sources	High-vacuum: 929*, 934, Multipliers: 931-A*, 1P21	Blue light. Very sensitive to incandescent light at a color temperature above 2700°K.
For ultra-violet measurement	High-vacuum: 935, 1P28	Same as above, but special glass envelope permits high ultra-violet sensitivity

*An RCA Preferred Type Tube

Color response curves are available on all RCA phototubes.

Vacuum-or Gas-or Multiplier-Type? Several important factors to be considered in selecting the general type of phototube for a service are given in the following table. Specific values should be considered in selecting the actual tube type.

Send for this valuable data

Free to electronics engineers: "RCA Phototube Booklet," complete with 11 typical circuit diagrams, curves, tables, and clearly written text. Address:

RCA, 716 South Fifth Street, Harrison, N. J.

Please send free phototube data to:

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What Phototube Do You Need?

Due to space limitations, the suggestions presented here are brief and in a condensed, summary form. If you have a specific application problem or wish to discuss your phototube requirements with us, write to RCA, Commercial Engineering Section, 716 Fifth Street, Harrison, N. J. For further published information on RCA Phototubes and how to use them, send the coupon at left.

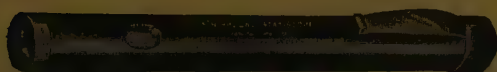
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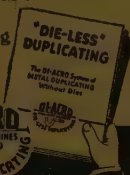
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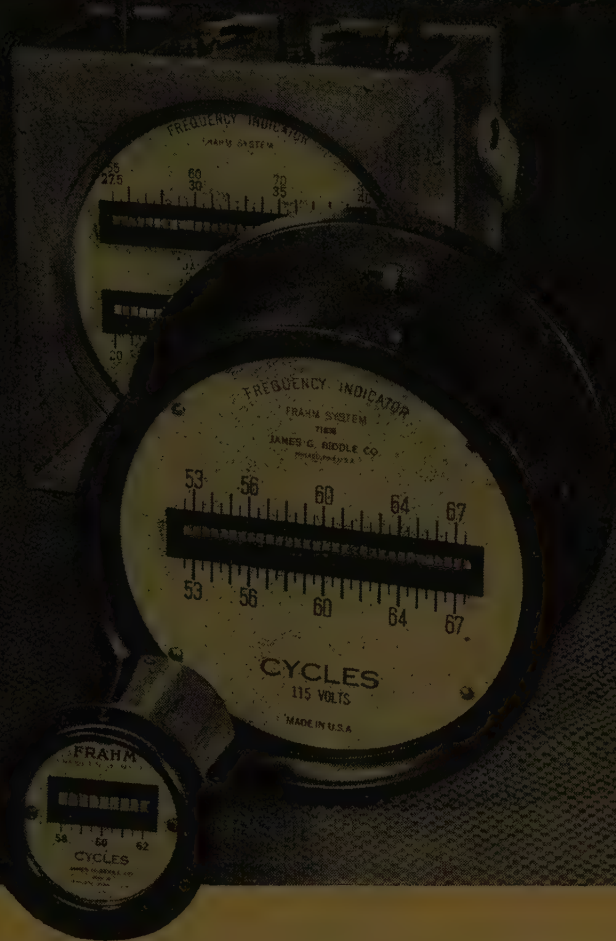
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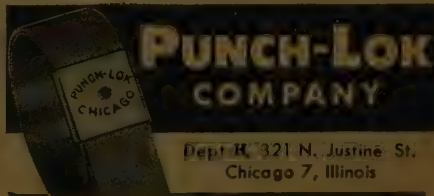


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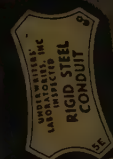
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The present scheduling system at times results in considerable inconvenience to our customers, we know. The whole purpose of the system, however, is to supply war materials when and where they are most urgently needed at the moment. This after all seems to be the basic aim of war production, doesn't it?

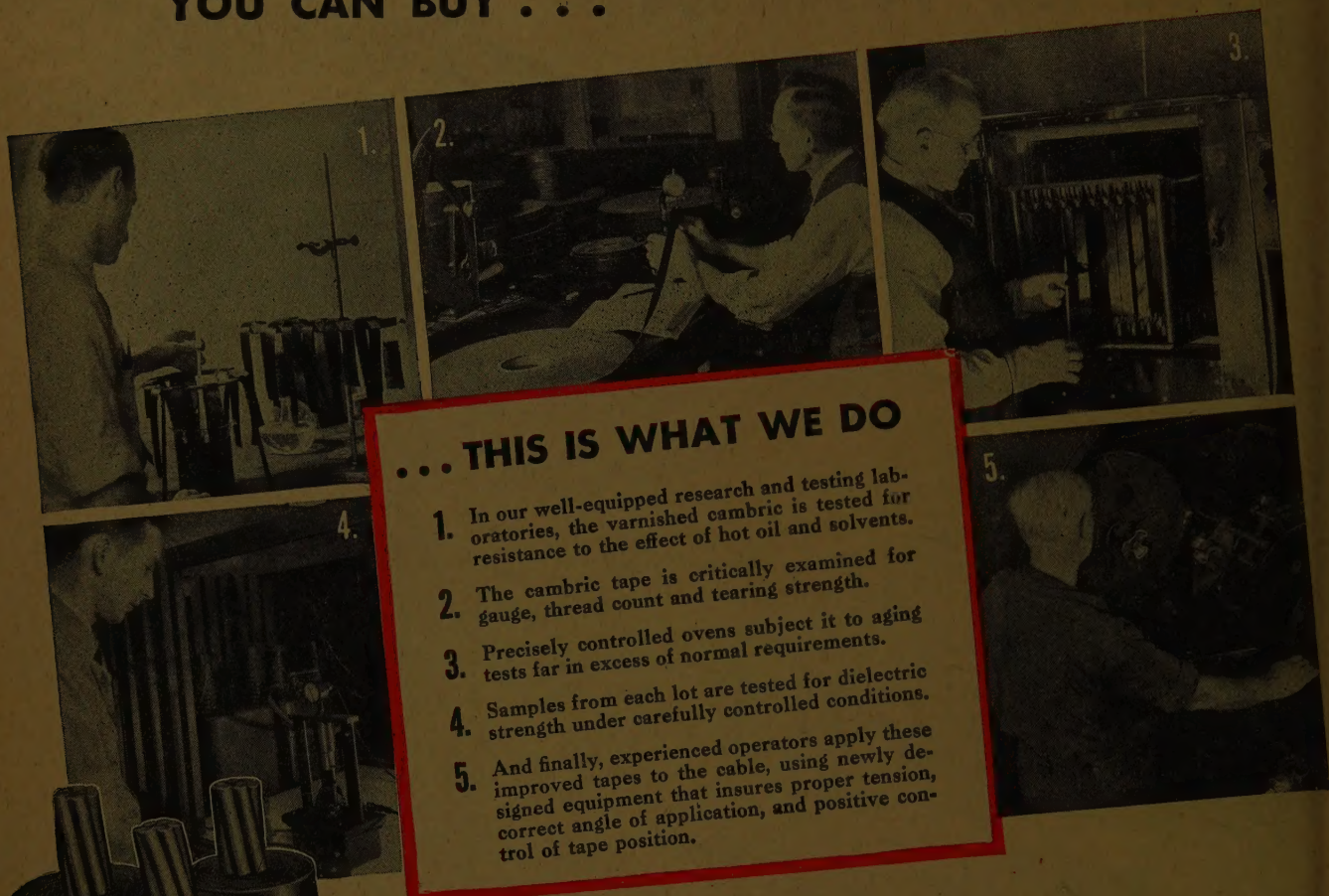


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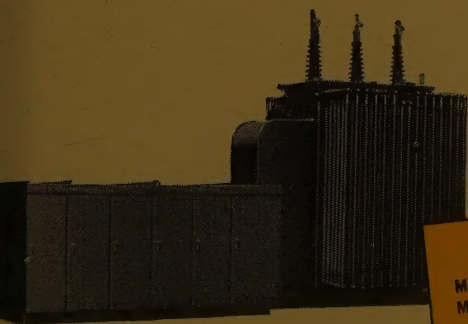
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● Specifying and ordering have been reduced to a simple routine that is comparable to changing the figures on a date stamp. Time saved on detailed specification work is available for more thorough system planning.

● Installed costs are lower, substantially so when factors such as reliability, safety, and high salvage value are included in the economic balance.

Remember, too, that General Electric's policy of repetitive manufacture *has not* resulted, and *will not* result, in a "freezing" of designs. Our research and design staffs can concentrate on improving the line as a whole rather than continually working out detail modifications in design to meet the specifications of each new order.

As you plan for new substation installations, let us work with you on this route to lower investment costs. *General Electric Company, Schenectady 5, N. Y.*



typical G-E master unit substation

THE BUILDER APPLIES
More fundamental design time per model
More production efficiency per hour



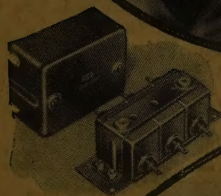
THE BUYER GAINS
More kva capacity per investment dollar
Less maintenance cost per year

Save Money and Buy More War Bonds

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HERE ONE MUST HEAR!

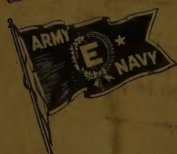
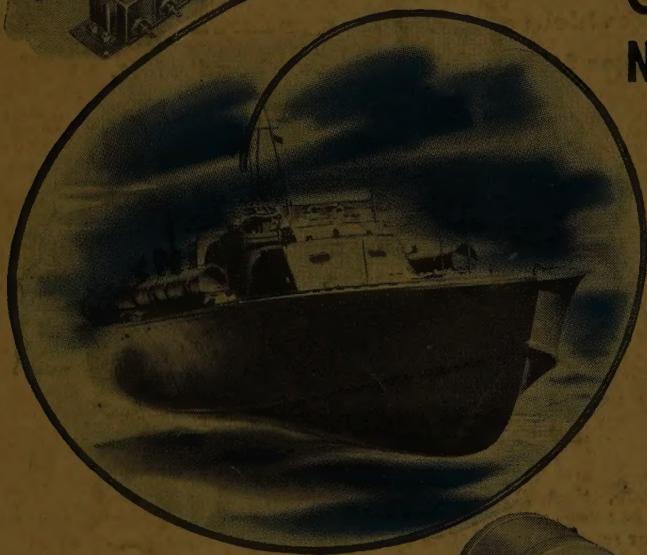


Combined Operations Demand Noise-Free Radio Channels

Upon reception and transmission of radio commands . . . upon freedom from local static's message-mangling crashes . . . may depend the timing which makes combined operations successful.

On every front, Solar Elim-O-Stat Filters are keeping speech channels clear . . . absorbing local interference where it starts . . . at motors, generators, contacts.

Severe seasoning under combat conditions gives Solar engineers war-proved products to study, helps prepare for industry's "combined operations" when world skyways, seaways and railways again are routes of neighbor-to-neighbor trade. Let Solar advise you on radio-noise suppression. Solar Manufacturing Corporation, 285 Madison Ave., New York 17, N. Y.



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